synchronization. Increasing or decreasing the power level allowed the system to regain synchronization. At this signal level, switching to the x2 mode would allow the STIC receiver to acquire the signal and maintain synchronization. This behavior did not occur at any power level during the x2 testing. MITRE personnel suggested this behavior was the result of a STIC receiver program error. The direct effects of this error on STIC field performance are unknown. However, the minimum signal power encountered during the field testing was -84 dBm, significantly greater than the -95 dBm power level at which the malfunction occurred.

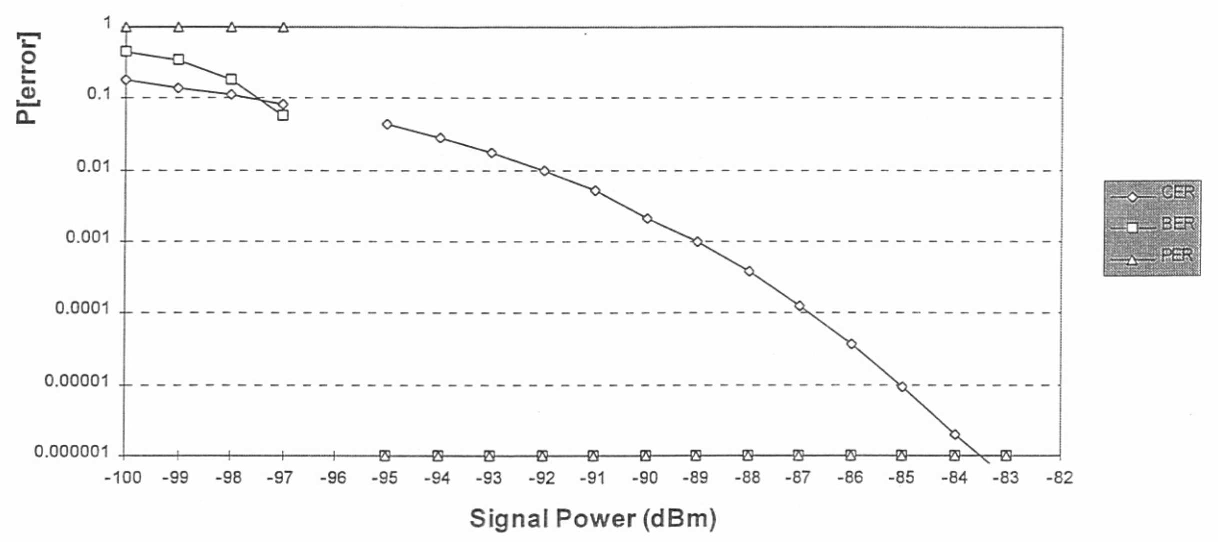

Figure 4. CER, BER, and PER vs. received signal power for x1 interleaver.

4. STIC FIELD TESTING AND EVALUATION

Once the laboratory testing of the STIC system was complete, a field test program was initiated. The primary goal of the field test program was to correlate the STIC performance with received signal level in a variety of reception environments.

4.1 STIC Installation

The following two subsections describe the installation and configuration of the STIC transmitter, STIC receiver, and signal power measurement system (Figure 5).

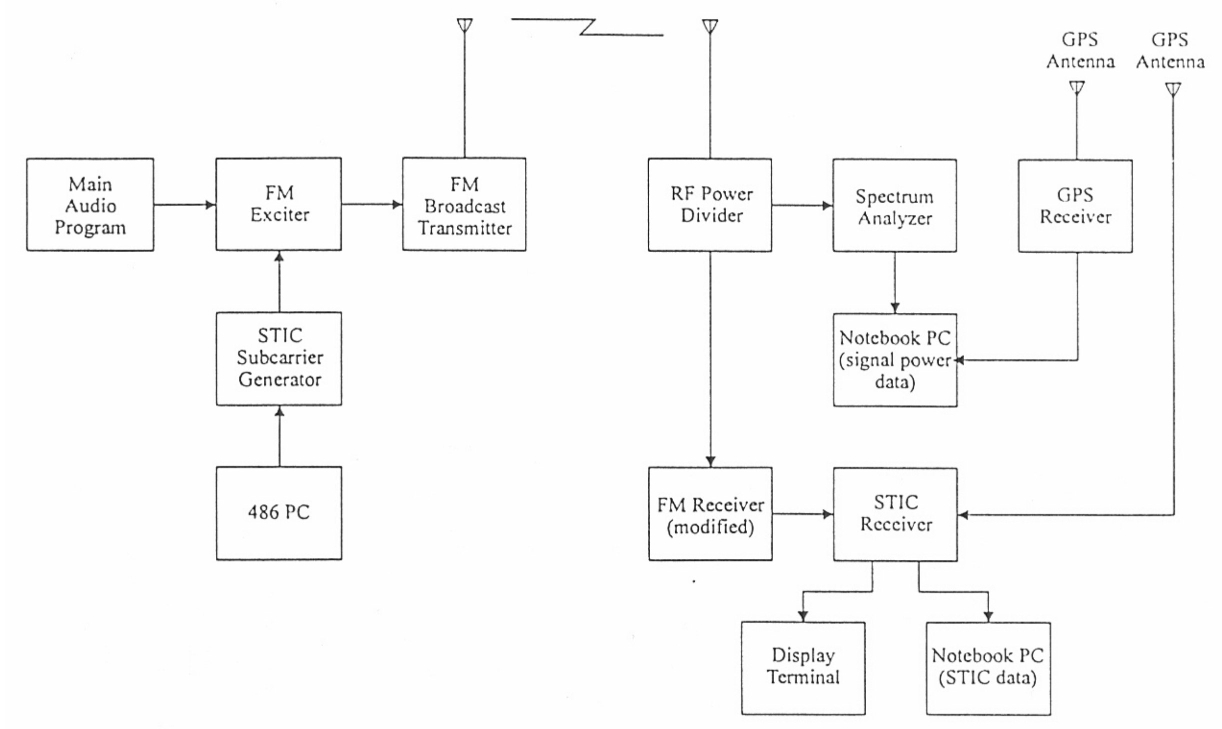

Figure 5. STIC field test configuration.

4.1.1 Transmitter

A local FM radio station agreed to participate in the STIC field testing program. The STIC transmitter was installed at the transmitter site of KYGO-FM, a Denver-area commercial FM radio station broadcasting with an effective radiated power of 100 kW and at a frequency of 98.5 MHz. The KYGO transmitter is located roughly 25 miles west of Denver, Colorado (altitude 5,280 feet), at an altitude of 10,597 feet. The transmitter site provides an unobstructed path into much of the Denver metropolitan area and to the East. The STIC signal was injected into the broadcast signal at a 10% injection level. The subcarrier injection level was set at the transmitter site by momentarily interrupting the entertainment signal and measuring the total modulation on the transmitter's modulation meter. No other subcarriers were carried by the station. The program format is country-western.

The STIC system can operate using a variety of interleaver sizes. At the time of the STIC transmitter installation, NTIA/ITS and MITRE personnel decided to operate the STIC system in the default x1 mode. This mode was chosen because the transmitter site had encountered occasional power outages due to severe weather conditions and in the event of a power cycle, the STIC transmitter would automatically resume operation in the default x1 mode. The transmitter site is a considerable distance from Boulder, Colorado and there were no provisions at the transmitter location for remote configuration of the STIC system.

4.1.2 Receiver

In order to efficiently measure STIC performance over a wide geographical area, a mobile data collection system was employed. The data collection system consisted of a van with both the STIC receiver system and signal power measurement systems (Figure 6). GPS receivers were employed by both systems allowing the simultaneous collection of received signal power, STIC performance, time, and location. The STIC receiver was configured to utilize the x1 interleaver. Appendix A provides details of the measurement system and Appendix B details the data-processing methodology.

Figure 6. Mobile data collection van.

This report describes the STIC performance as a function of received signal power. In some cases, electric field strength is a more useful parameter with which to correlate system performance. Appendix C describes the procedure for conversion from received signal power to electric field. strength.

4.2 Route Planning

The metropolitan Denver area provides a wide variety of natural and man-made reception environments in which to evaluate the STIC performance. Denver, Colorado, is located on the plains of the American Mid-West, 20 miles east of the dramatic rise of the Rocky Mountains. Its location provides four areas in which the STIC system may operate. These areas were defined as: urban high-rise, deep canyons formed by long rows of high-rise buildings; urban low-rise, areas of significant numbers of buildings roughly 1 or 2 stories high; rural plains, great open areas typically devoid of significant structures or dramatic terrain features; and rural mountains, areas dominated by tall mountains and deep natural canyons. The two urban environments encompass typical urban and suburban areas while the two rural categories cover most rural environments.

A series of driving routes was chosen to provide significant time in each environment and to define the boundaries of coverage by increasing the distance from the transmitter. The table below summarizes each environment, lists the number of miles over which data were collected, and provides a color key for each environment that corresponds to the map in Figure 7.

Reception Environment Data and Map Color Key

Environment	**Miles**	**Map Key**	**Characteristics**
Transmitter	N/A	Orange	Mountain-top location.
Urban High-Rise	16.4	Pink	City streets, urban canyons, high-rise corridors.
Urban Low-Rise	117.0	Yellow	Significant man-made obstacles and obstructions, typically no greater than 2 stories tall.
Rural Mountain	130.0	Green	Deep canyons, rugged terrain, significant terrain shadowing.
Rural Plains	330.0	Blue	Few significant natural or man-made obstacles. Typically line-of-sight.

Figure 7. Map of data collection routes.

4.3 STIC Field Evaluation

For each environment described above, several statistics of performance were computed and analyzed. In a dynamic signal environment, such as experienced by a mobile receiver, the received signal was likely to experience significant degradation and distortion as the mobile receiver changed location. In certain locations, the signal degradation will be so severe that the reception of any data was impossible. It was in these areas that the STIC system would lose synchronization with the transmitter and thereby lost the ability to receive message or BER data. When the receiver was moved to a location more favorable to signal reception, the STIC system would regain synchronization. However, the effect of losing synchronization extended beyond the period of degraded signal reception. Upon moving to a location more favorable to signal reception, the STIC system would re-establish synchronization after an initialization period of approximately 15 seconds (for the x1 interleaver). During this resynchronization period, message or BER data were not being accepted and therefore the error rates (CER, BER, and PER) were assigned their maximum value. Discussions with MITRE personnel suggested that the STIC synchronization performance would have improved if the x2 interleaver were used instead of the x1. Due to time and equipment constraints it was not possible to repeat the field data collection procedure for the x2 interleaver but by filtering the field performance data to remove the data points corresponding to the STIC system "out of sync," it was possible to evaluate an approximate upper bound on STIC synchronization performance. These figures are labeled as "SYNC Data" in the following sections.

In the following sections, three sets of statistics are presented as a function of received signal power: mean error rate, median error rate, and percentile error rate. Additionally, mean and percentile error rates are presented in the "SYNC Data" form and several other statistics are computed and presented. No one statistical or performance measure can evaluate or quantify the performance of a complex communication system such as the STIC. Each statistical estimation of STIC performance provides unique insight into the system performance.

4.3.1. Rural Plains Environment

Data for the rural plains environment were collected over paths totaling 330 miles. These data were collected at distances between 25 and 103 miles from the transmitter and consisted of 4,127 signal-power and STIC error-rate measurement locations. The propagation environment was typically either line-of-sight or close to line-of-sight. Few significant geographical features or man-made obstacles were present.

Figure 8 displays mean error rates vs. received signal power. The mean error rates for a specific signal power level were calculated by forming the arithmetic mean of channel, bit, and packet error rate measurements for a specific power level (± 2 dB) and placing them in the appropriate bin. Figure 9 displays the same data set with the out-of-sync errors removed. The removal of these data points produced an improvement of approximately 8 dB in STIC performance.

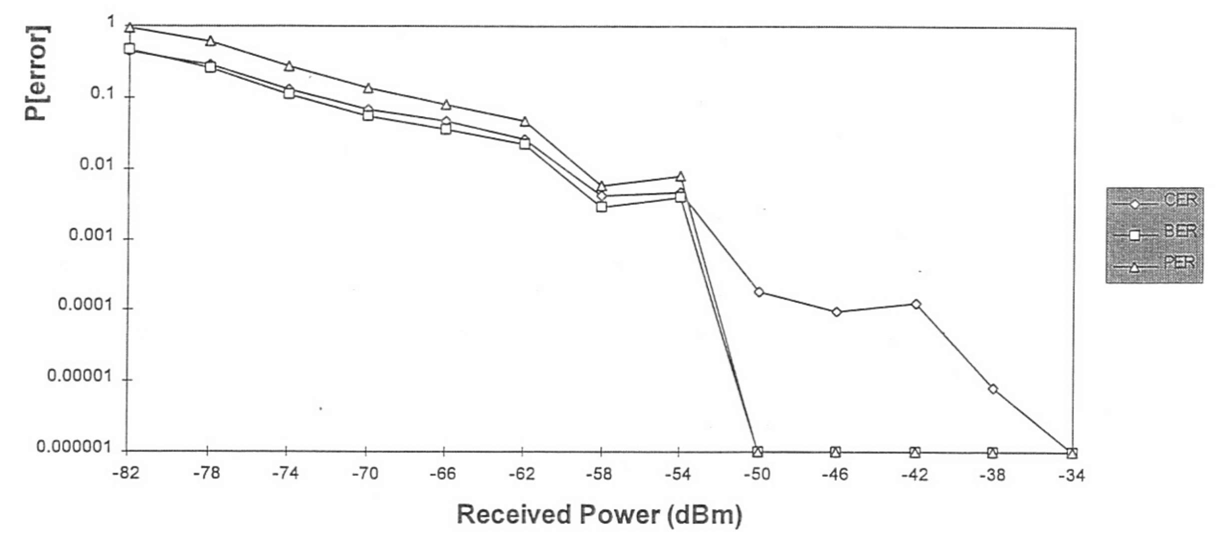

Figure 8. Mean CER, BER, and PER vs. received signal power for rural plains environment.

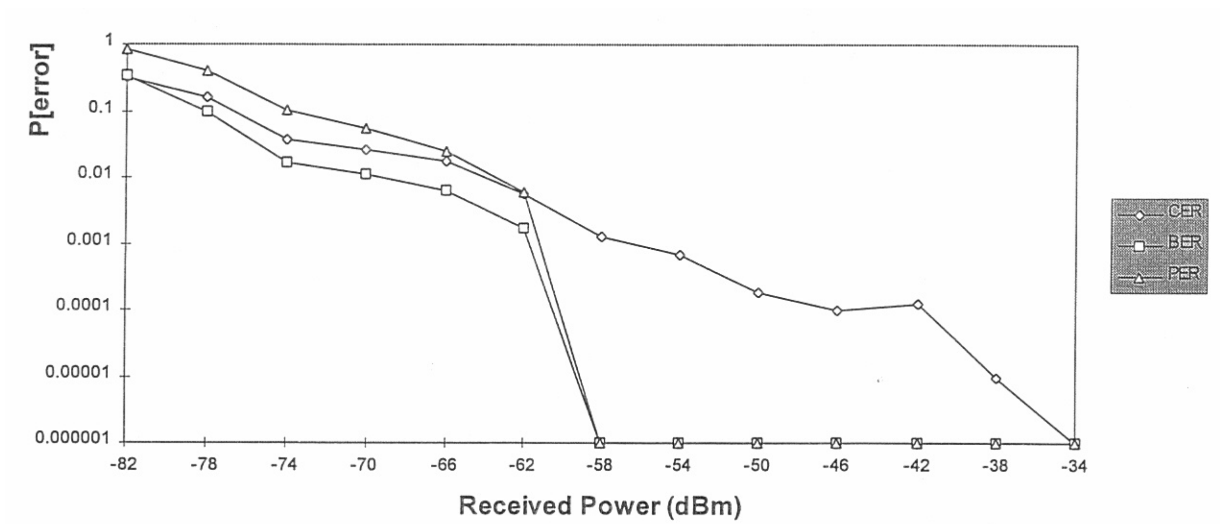

Figure 9. Mean CER, BER, and PER vs. received signal power (SYNC data) for rural plains environment.

Figures 10, 11, and 12 show the STIC performance data using median and percentile error rates vs. signal power. Median and percentile error rates assist in illuminating the almost binary nature of STIC PER performance, where errors typically occur in bursts.

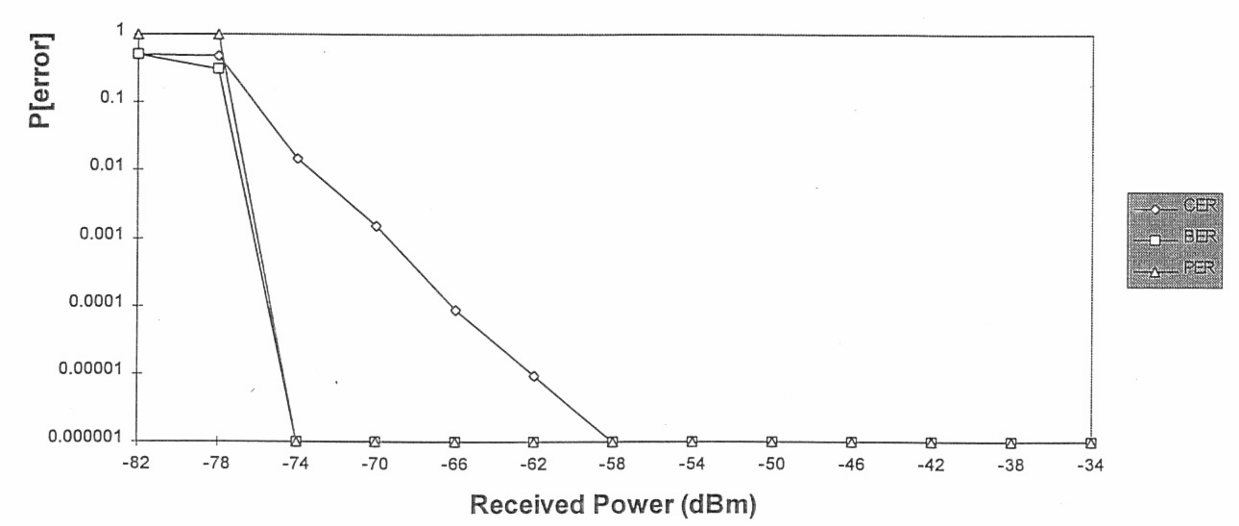

Figure 10. Median CER, BER, and PER vs. received signal power for rural plains environment.

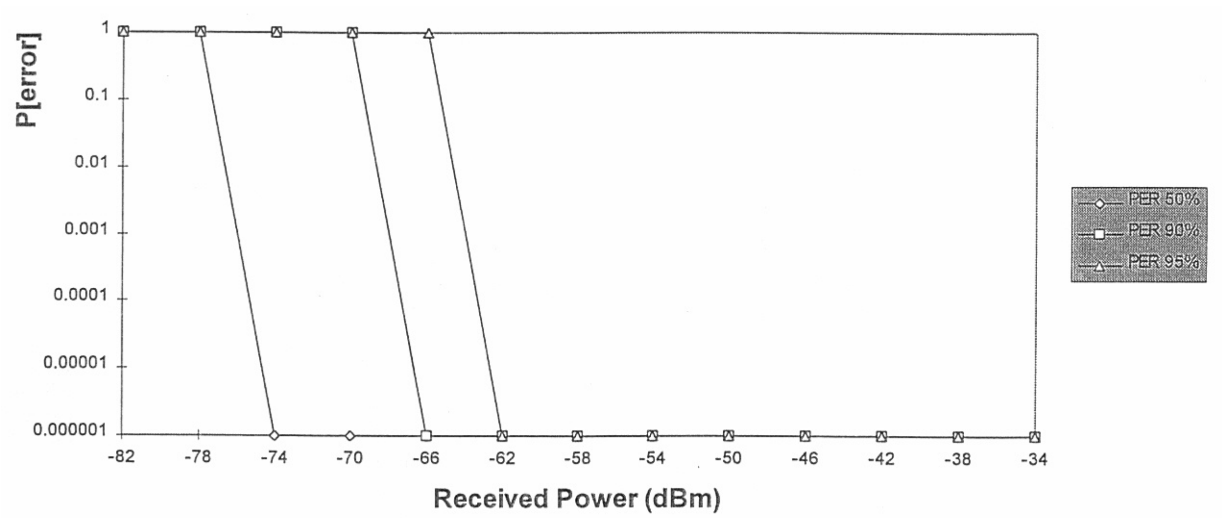

Figure 11. Percentile packet error rates vs. received signal power for rural plains environment.

Figure 13 displays mean error rates vs. distance from the transmitter. The error rates were computed in the same manner as the data in Figure 8 except that error rate measurements were sorted by distance instead of power level. It was interesting to note the dramatic decrease in STIC performance at the ranges of 33 miles, and 43 to 51 miles. Examining the scatter plot of signal power vs. distance (see Figure 17), there were instances of unusually low signal power at 33 miles, a significant group in the range of 43 to 51 miles, another group in the range of 65 to 77 miles, and above 85 miles. These power levels (< -70 dBm) were consistent with high packet error rates shown in Figures 8 through 12.

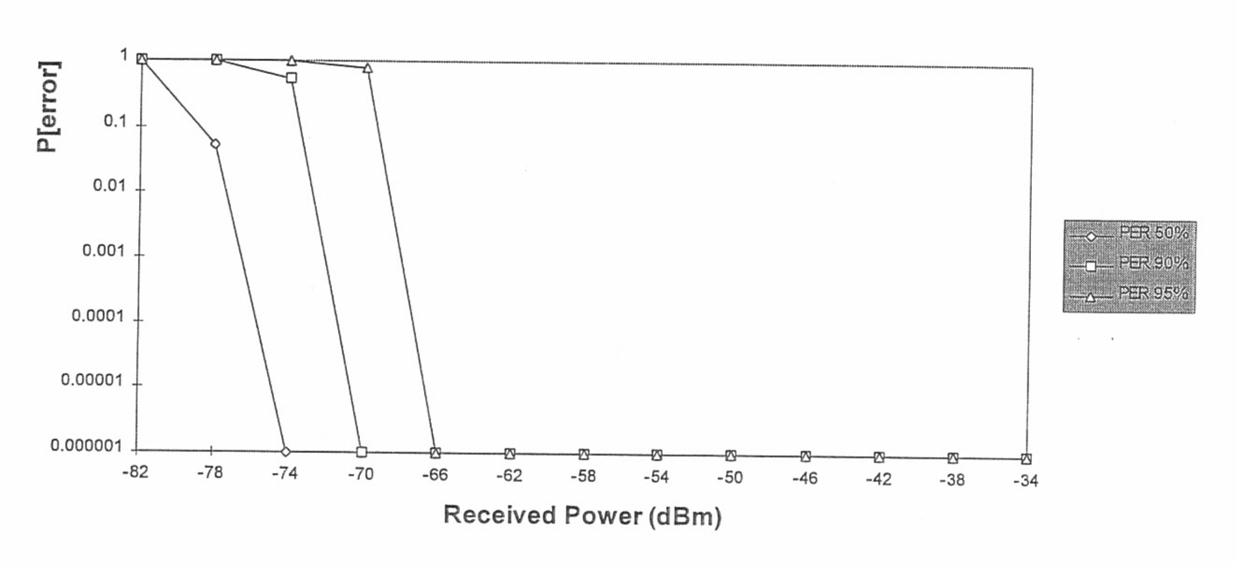

Figure 12. Percentile packet error rates vs. received signal power for rural plains environment.

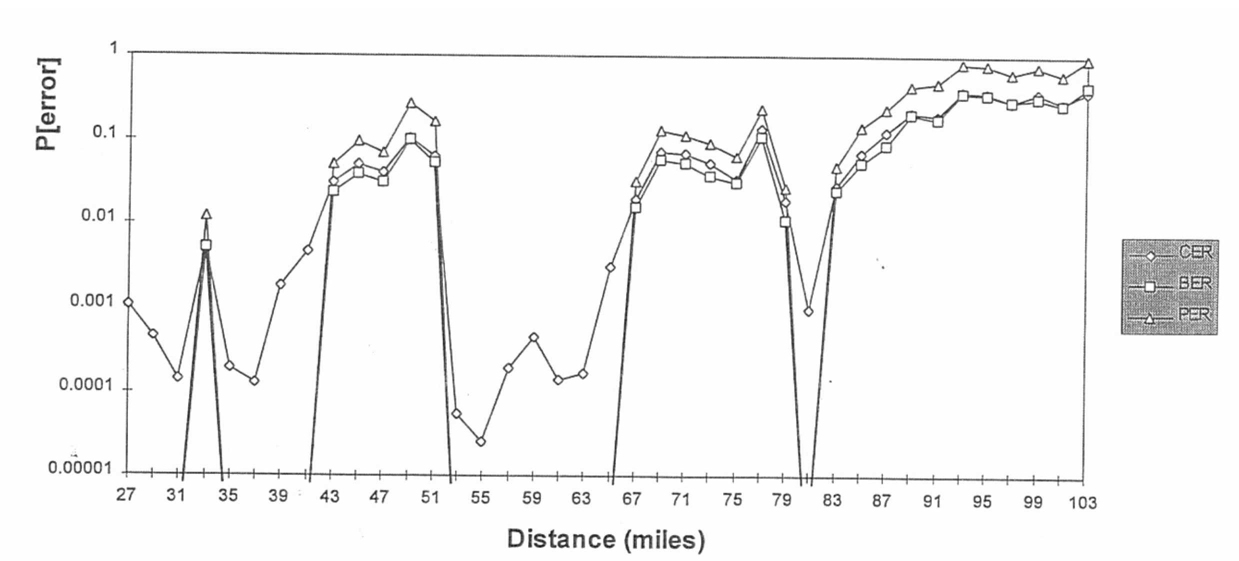

Figure 13. Mean error rates vs. distance from transmitter for rural plains environment.

Figure 14 displays cumulative error rates vs. error rate for the three performance metrics and Figures 15 and 16 display the raw channel and packet error rate data in the form of scatter plots. It was from these scatter plots that the mean, median, and percentile error rate plots were generated.

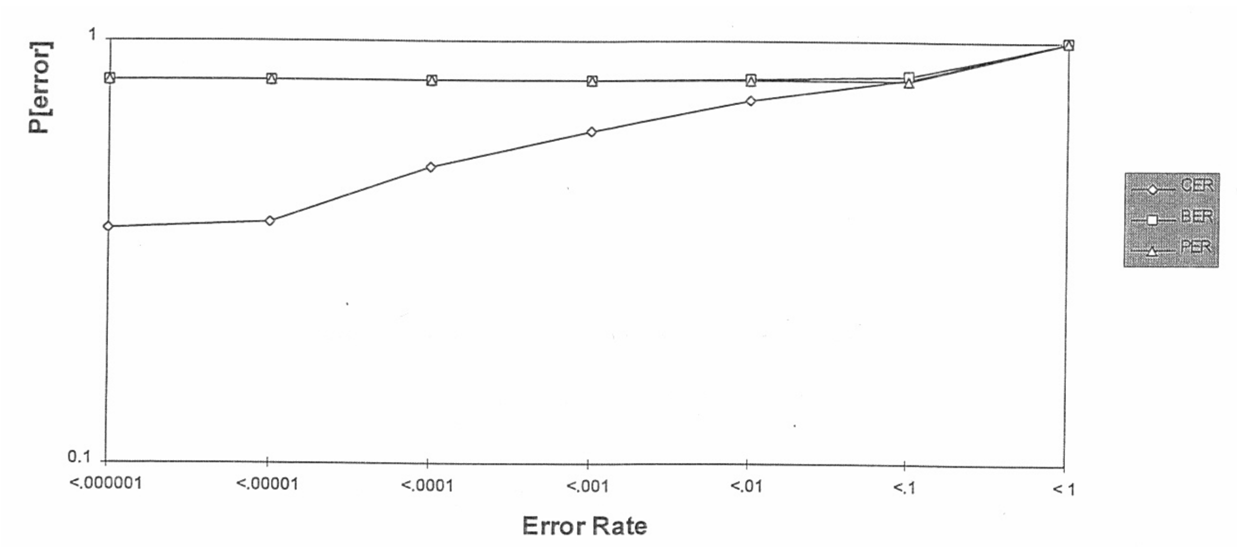

Figure 14. Cumulative error rates vs. error rate for rural plains environment.

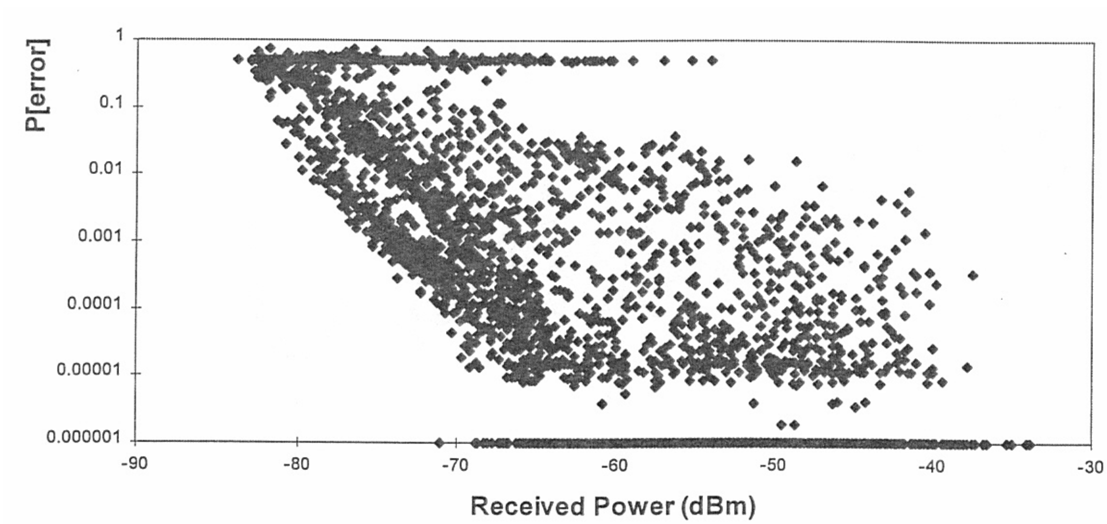

Figure 15. Channel error rates vs. received signal power for rural plains environment.

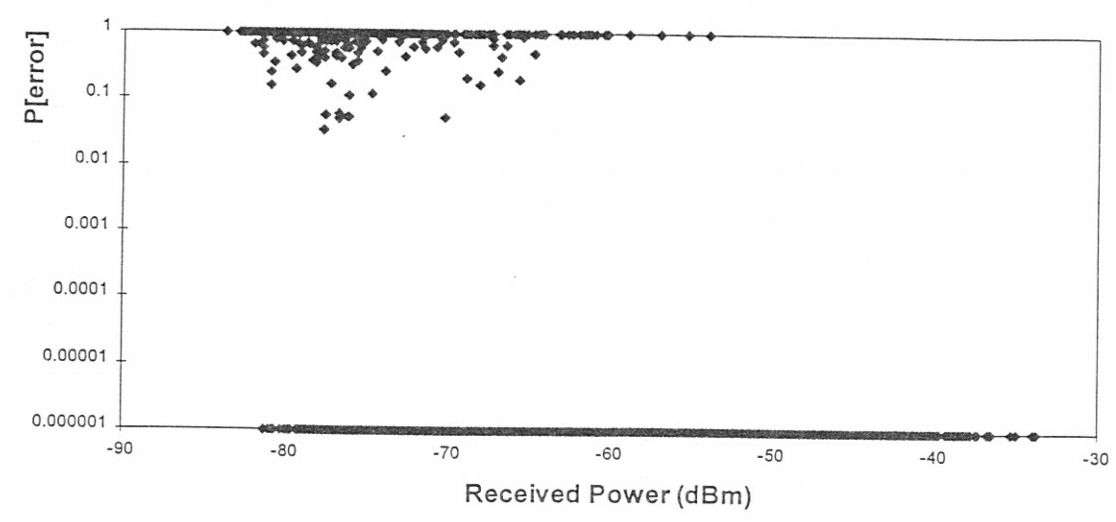

Figure 16. Packet error rates vs. received signal power for rural plains environment.

Figure 17 shows received signal power vs. distance to transmitter in the form of scatter plot. Figures 18 and 19 show the number of measurements used to construct each error rate estimate.

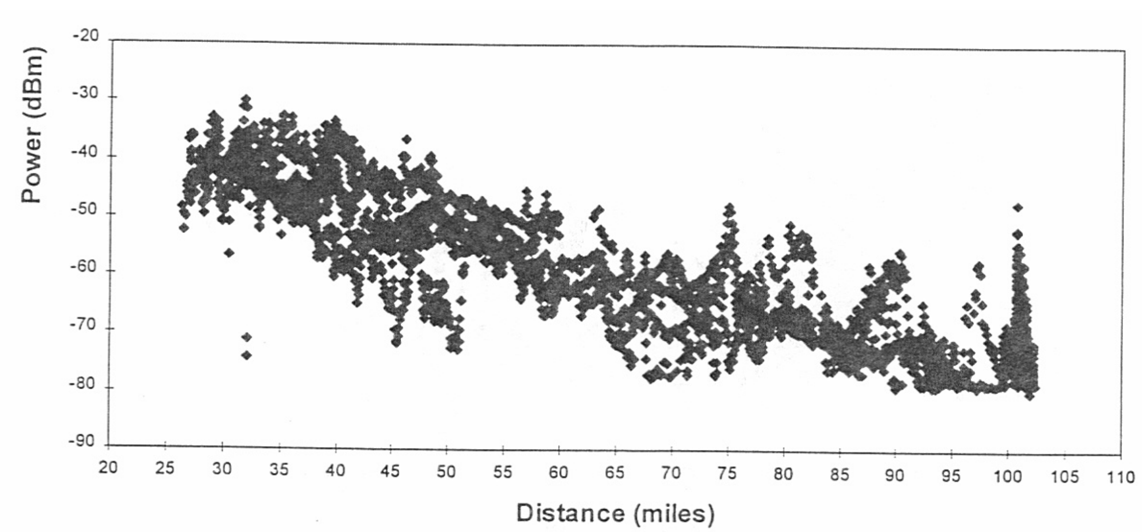

Figure 17. Received signal power vs. distance from transmitter for rural plains environment.

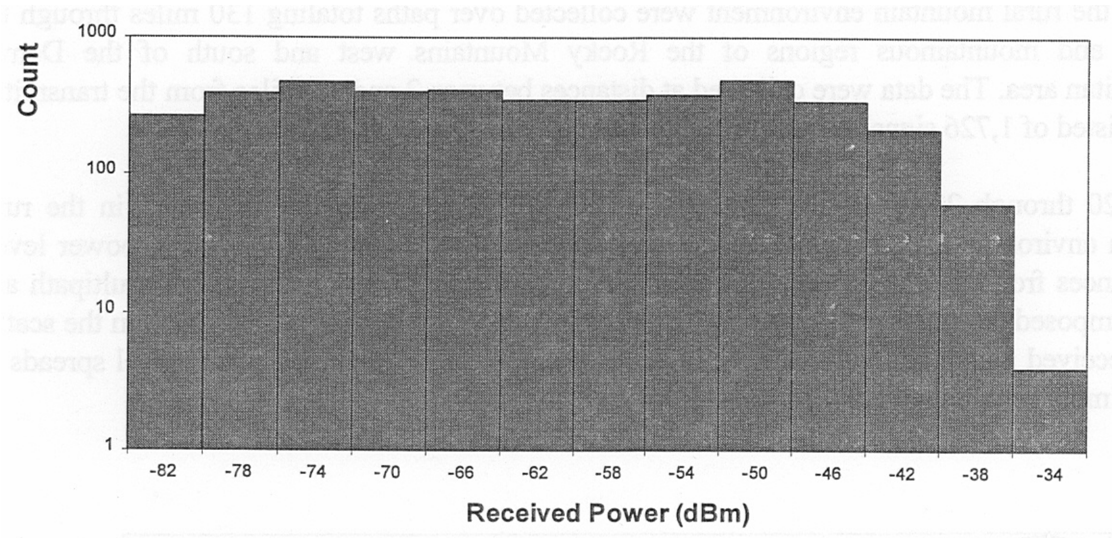

Figure 18. Measurement count vs. received signal power for rural plains environment.

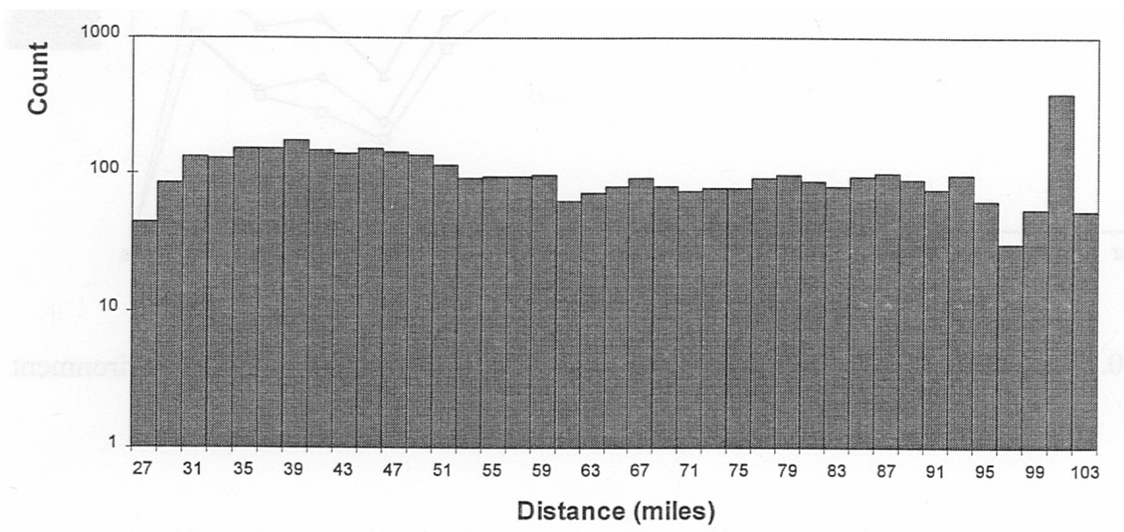

Figure 19. Measurement count vs. distance from transmitter for rural plains environment.

4.3.2 Rural Mountain Environment

Data for the rural mountain environment were collected over paths totaling 130 miles through the foothills and mountainous regions of the Rocky Mountains west and south of the Denver metropolitan area. The data were collected at distances between 2 and 48 miles from the transmitter and consisted of 1,726 signal-power and STIC error-rate measurements.

Figures 20 through 28 reveal the generally poor performance of the STIC system in the rural mountain environment. Error performance was poor over a wide range of received power levels and distances from the transmitter. This was not surprising considering the severe multipath and shading imposed on the STIC receiver. The severity of the environment was apparent in the scatter plot of received power vs. distance from transmitter (Figure 29). Received power level spreads of 60 dB or more for similar distances were common.

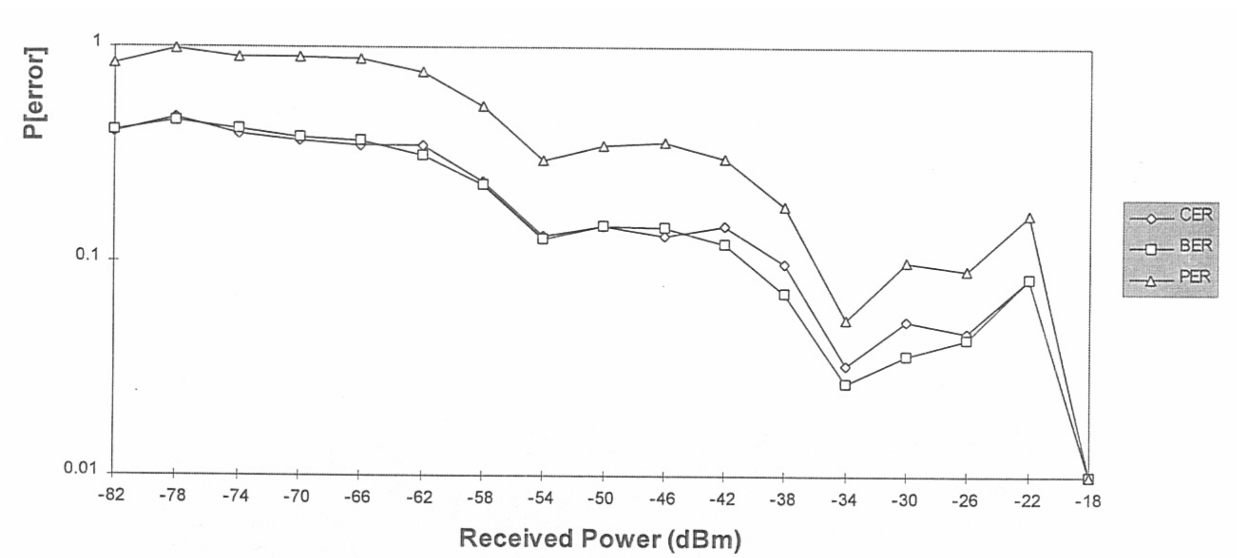

Figure 20. Mean CER, BER, and PER vs. received signal power for rural mountain environment.

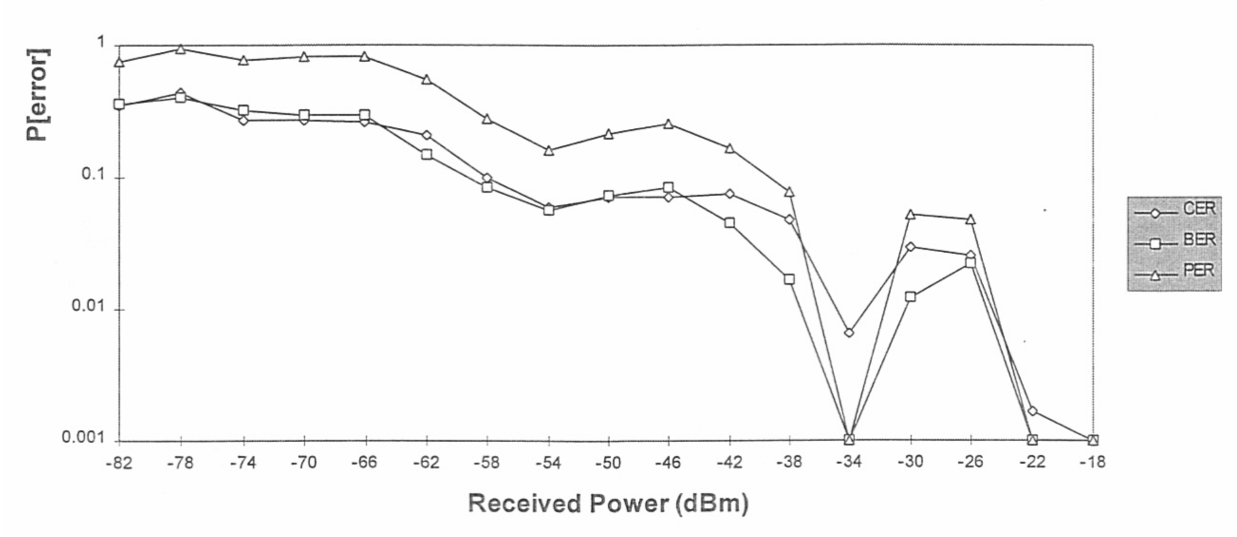

Figure 21. Mean CER, BER, and PER vs. received signal power (SYNC data) for rural mountain environment.

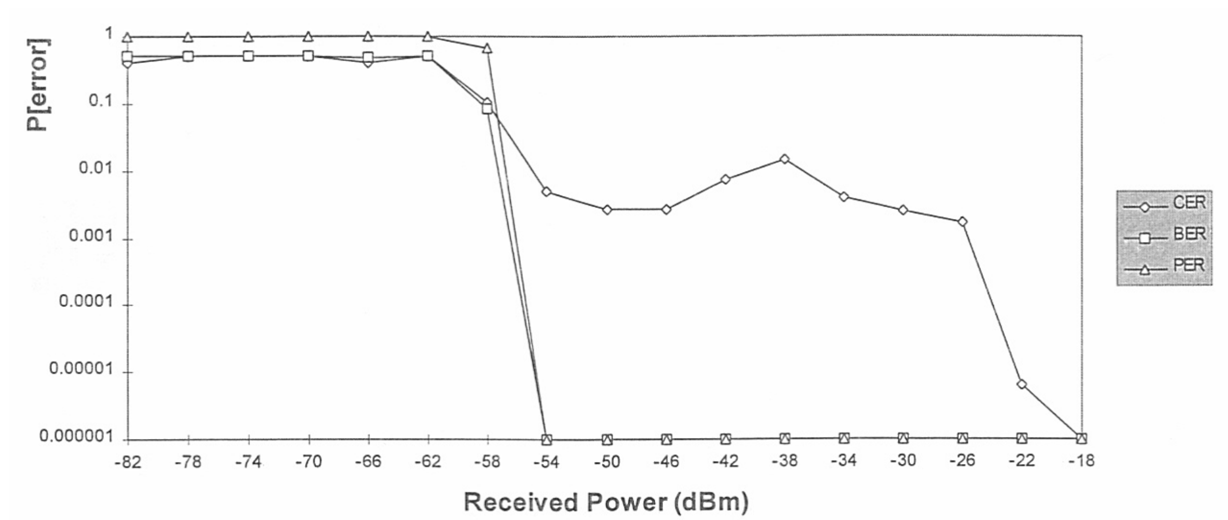

Figure 22. Median CER, BER, and PER vs. received signal power for rural mountain environment.

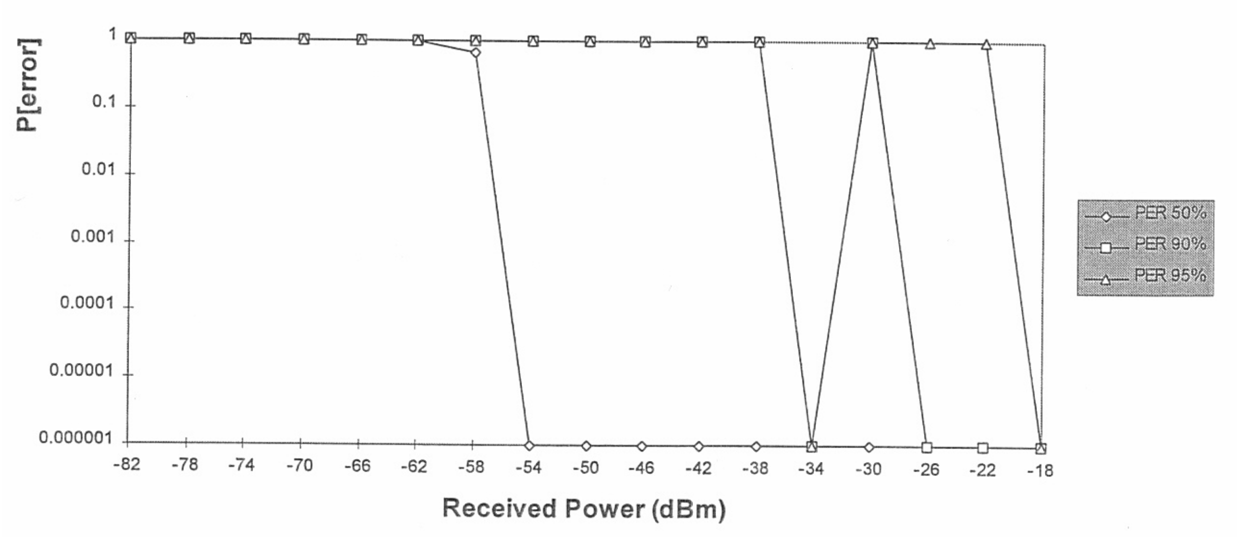

Figure 23. Percentile CER, BER, and PER vs. received signal power for rural mountain environment.

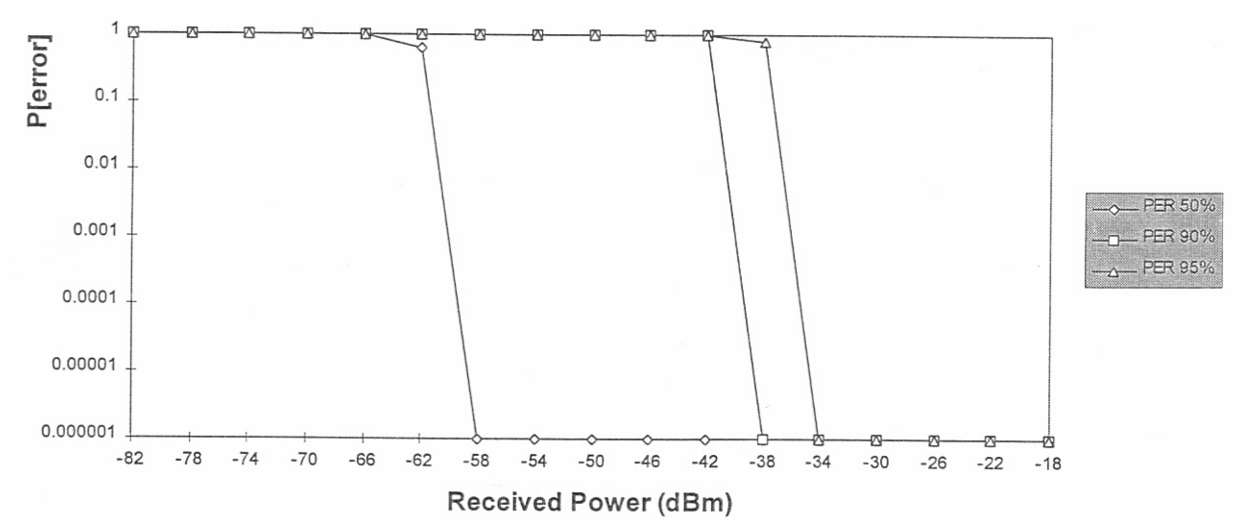

Figure 24. Percentile CER, BER, and PER vs. received signal power (SYNC data) for rural mountain environment.

In Figure 25 (Mean Error Rates vs. Distance from Transmitter) there appeared to be an inconsistency in the STIC error rate performance. At distances between 25 and 34 miles from the transmitter, the STIC system appeared to be operating error free. This inconsistency was explained by Figures 29 through 31 which show that very little data were collected at that distance.

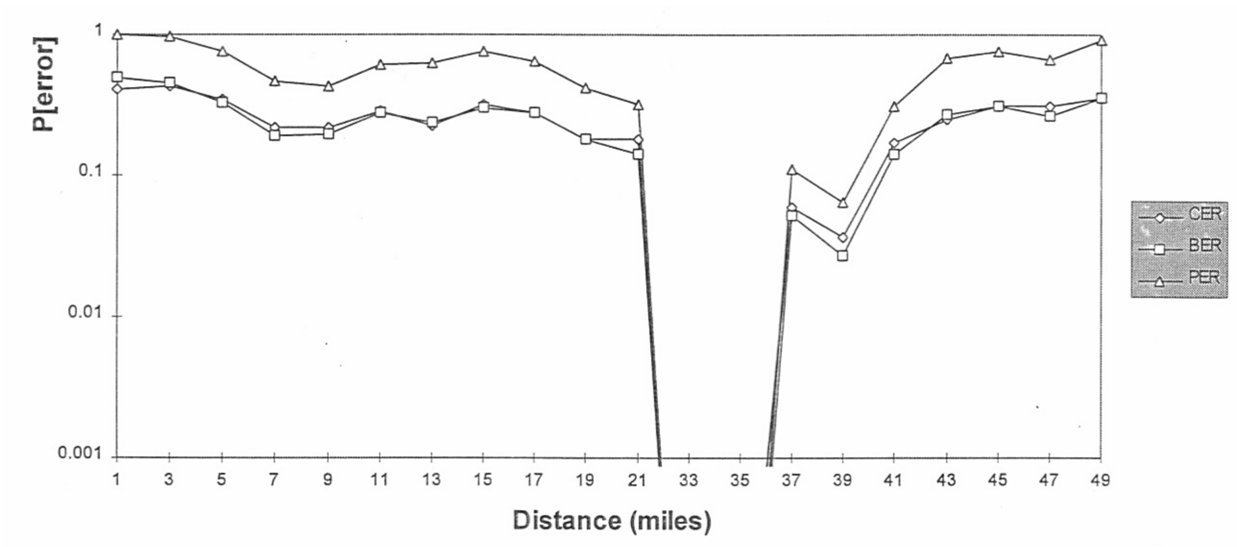

Figure 25. Mean CER, BER, and PER vs. distance from transmitter for rural mountain environment.

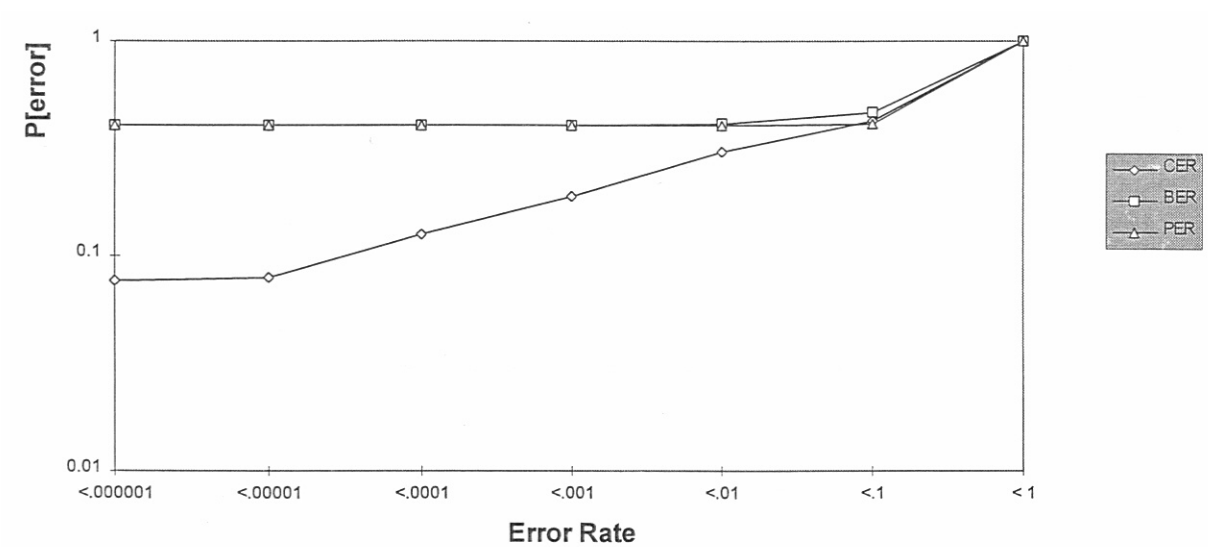

Figure 26. Cumulative error rates vs. error rate for rural mountain environment.

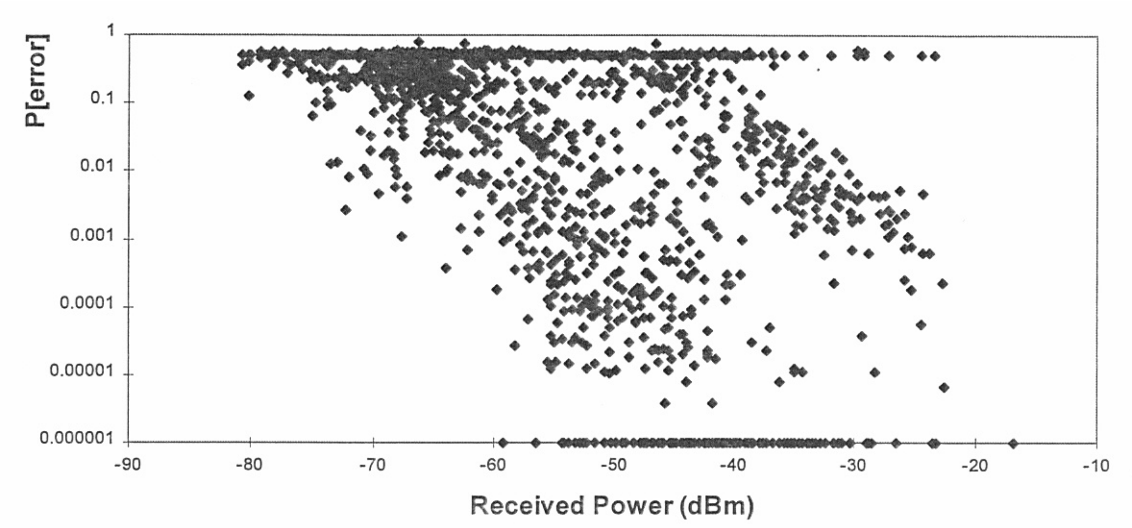

Figure 27. Channel error rates vs. received signal power for rural mountain environment.

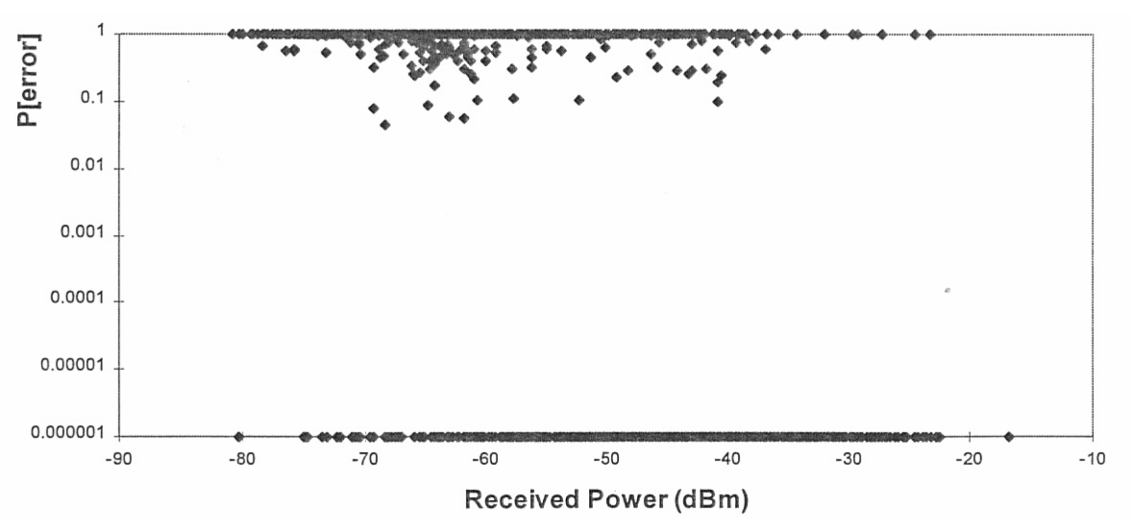

Figure 28. Packet error rates vs. received signal power for rural mountain environment.

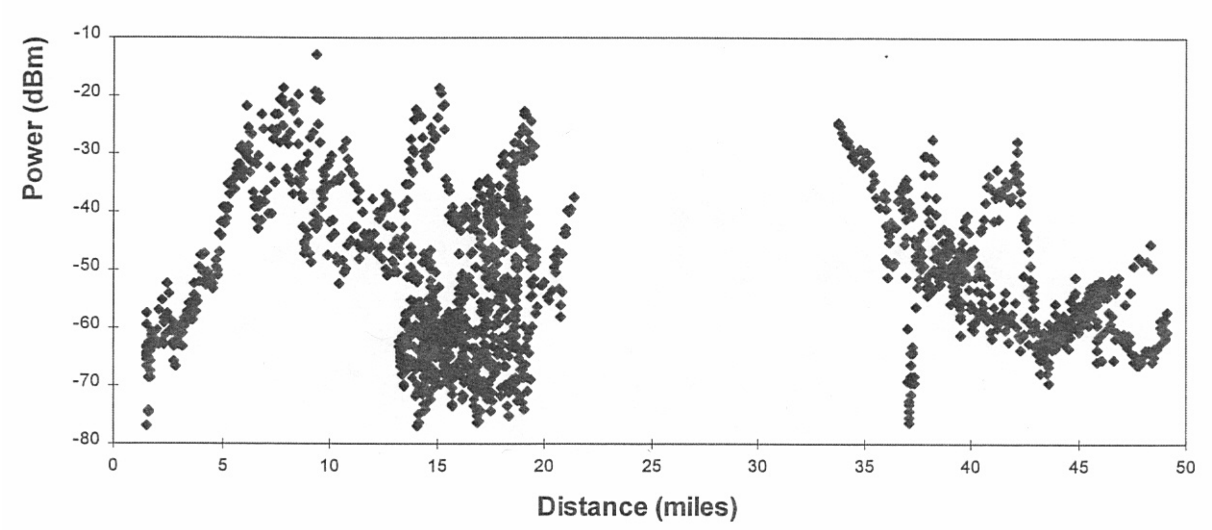

Figure 29. Received signal power vs. distance from transmitter for rural mountain environment.

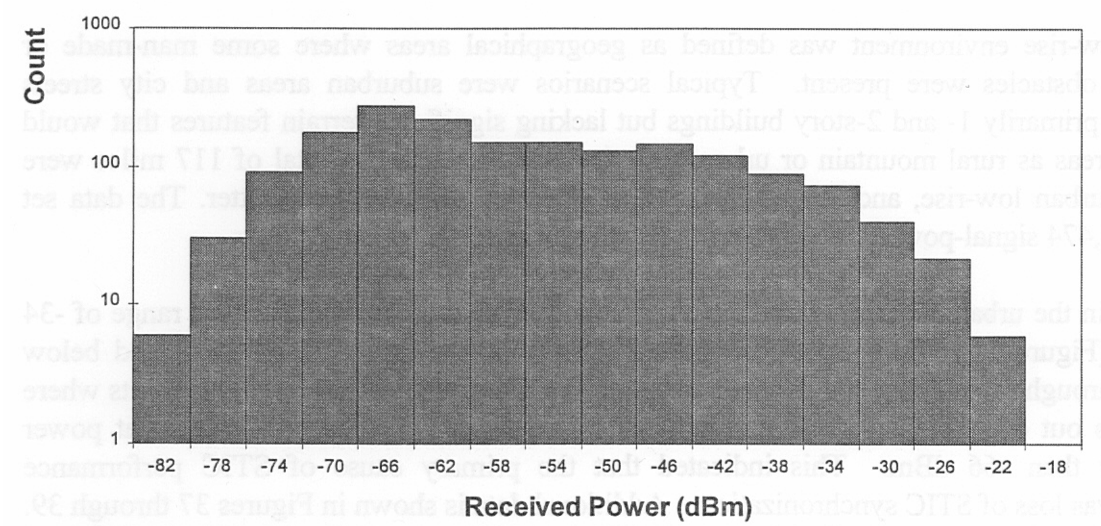

Figure 30. Measurement count vs. received signal power for rural mountain environment.

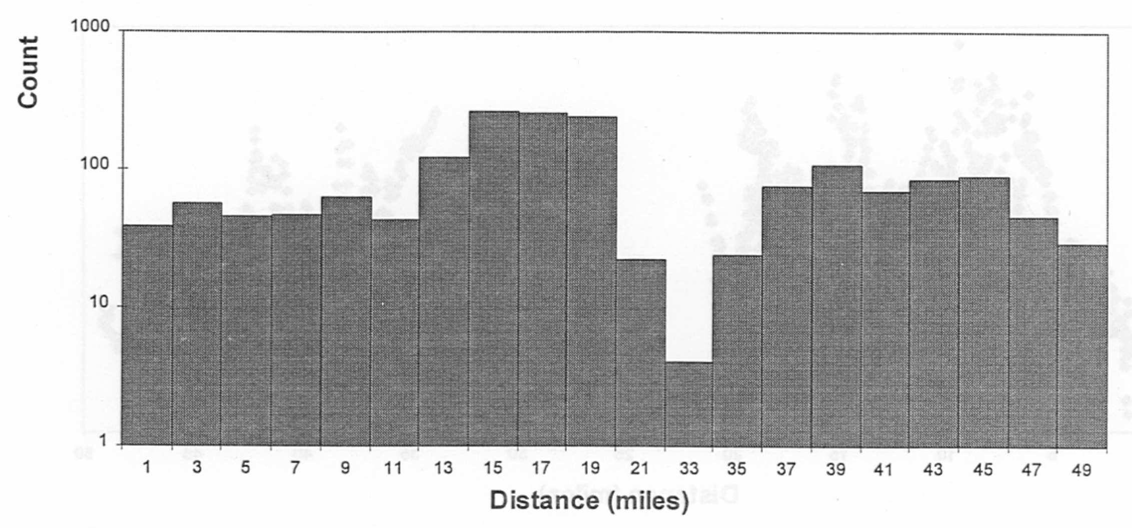

Figure 31. Measurement count vs. distance from transmitter for rural mountain environment.

4.3.3. Urban Low-rise Environment

The urban low-rise environment was defined as geographical areas where some man-made or geographical obstacles were present. Typical scenarios were suburban areas and city streets populated by primarily 1- and 2-story buildings but lacking significant terrain features that would classify the areas as rural mountain or urban high-rise environments. A total of 117 miles were classified as urban low-rise, and ranged from 17 to 47 miles from the transmitter. The data set consisted of 1,474 signal-power and STIC error-rate measurements.

Performance in the urban low-rise environment remained relatively constant over the range of -34 to -62 dBm (Figure 32). Error rates rose dramatically at power levels of -66 dBm and below (Figures 32 through 36), as they did for the rural plains environment. Removing data points where the STIC was out of sync resulted in a significant improvement in error performance at power levels greater than -66 dBm. This indicated that the primary cause of STIC performance degradation was loss of STIC synchronization. Additional data is shown in Figures 37 through 39. During resynchronization (nominally 15 seconds) CER and BER were defined as 0.5 and PER was defined as 1. This was evident in the scatter plot of PER vs. signal power (Figure 40). A high proportion of data points on the PER = 1 line corresponded to the STIC system being out of synchronization. It was clear that these points dominate the error behavior of the system. It was also interesting that these out-of-sync periods were apparently not highly correlated with received signal power.

Judging from Figure 37, STIC performance in the urban low-rise environment actually *improved* with increasing distance from the transmitter. Figure 37 shows packet errors occurring only at distances between 21 and 27 miles from the transmitter. This was likely due to the categorization of the data. Figure 7 shows that the shorter distance urban low-rise data were collected in an area contiguous with the longer distance rural mountain data. The scatter plot of received signal power vs. distance (Figure 41) shows a high variability in received signal power vs. distance in the range of 18 to 30 miles. This behavior was consistent with the rural mountain environment (Figure 29). Figure 41 suggests that perhaps the urban low-rise data in the range of 18 to 30 miles may be more accurately described as rural mountain environment.

Other than the inconsistency in the short-distance urban low-rise data, the performance of the STIC system in the urban low-rise environment was very similar to the performance in the rural plains environment.

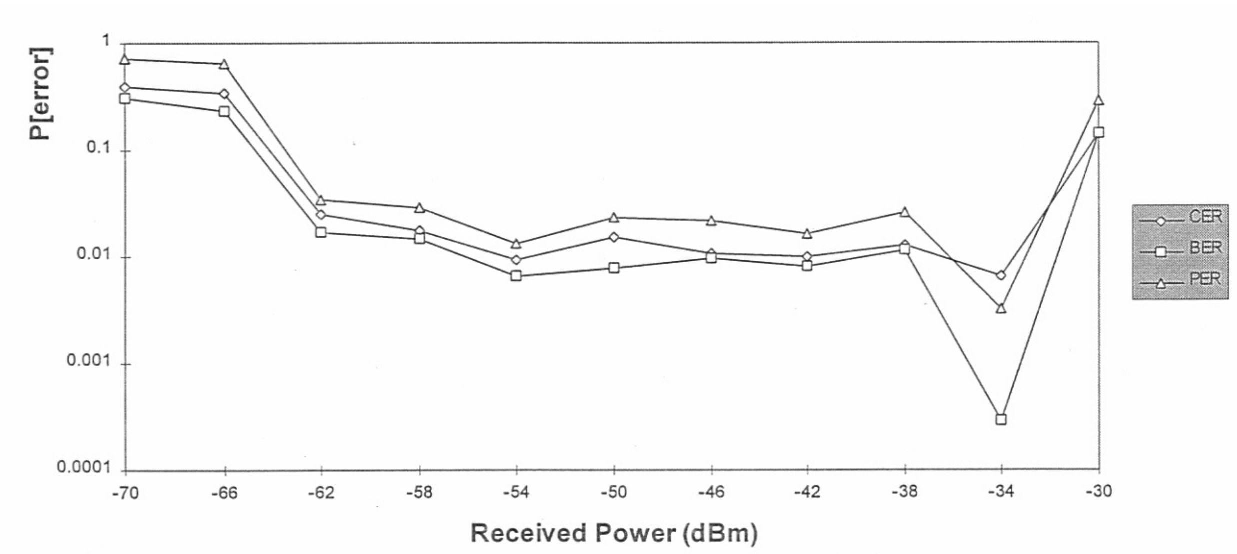

Figure 32. Mean CER, BER, and PER vs. received signal power for urban low-rise environment.

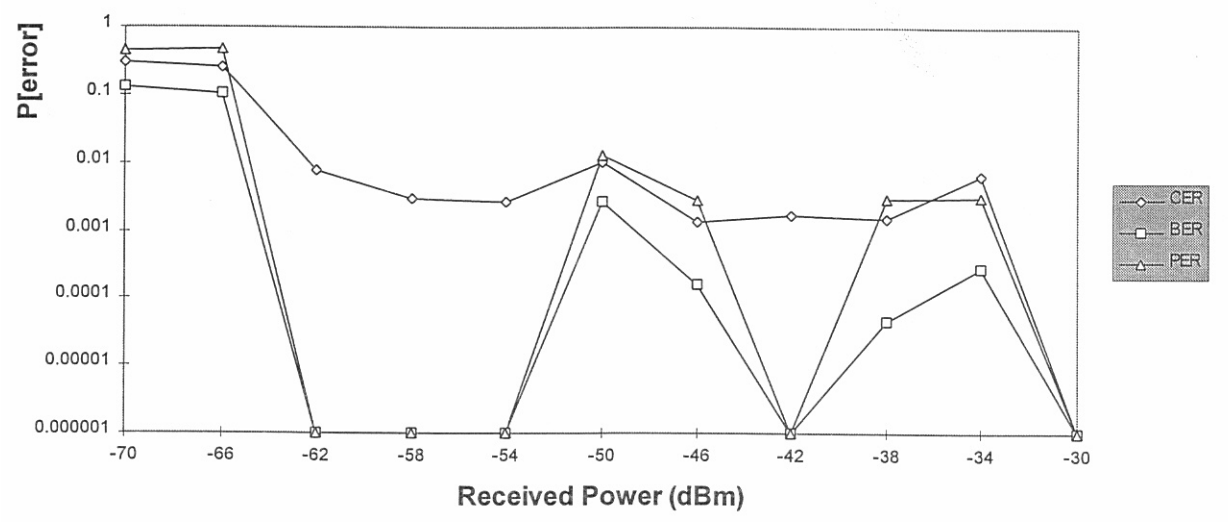

Figure 33. Mean CER, BER, and PER vs. received signal power (SYNC data) for urban low-rise environment.

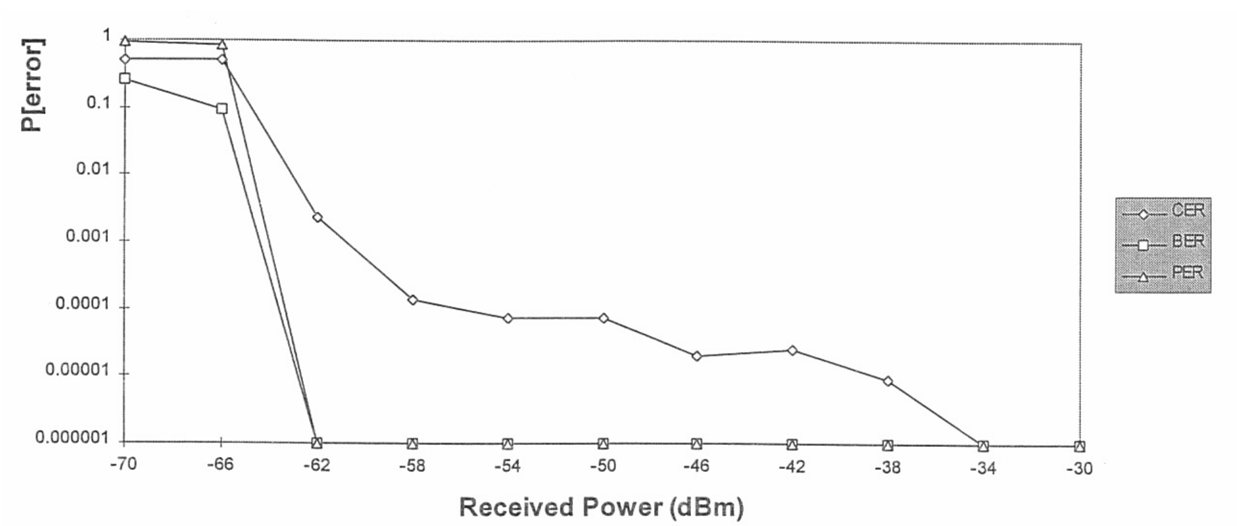

Figure 34. Median CER, BER, and PER vs. received signal power for urban low-rise environment.

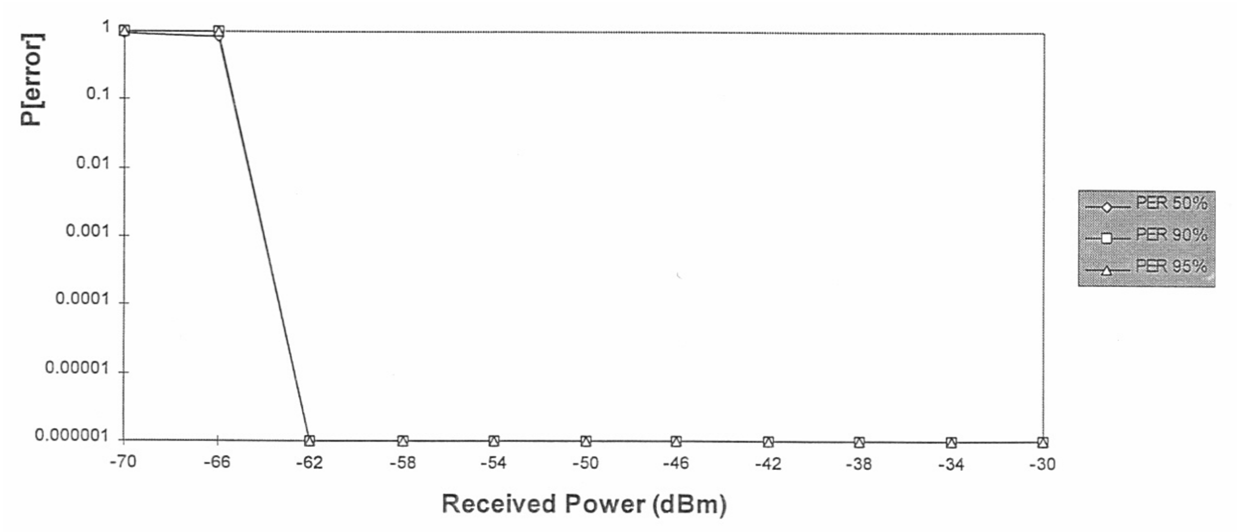

Figure 35. Percentile CER, BER, and PER vs. received signal power for urban low-rise environment.

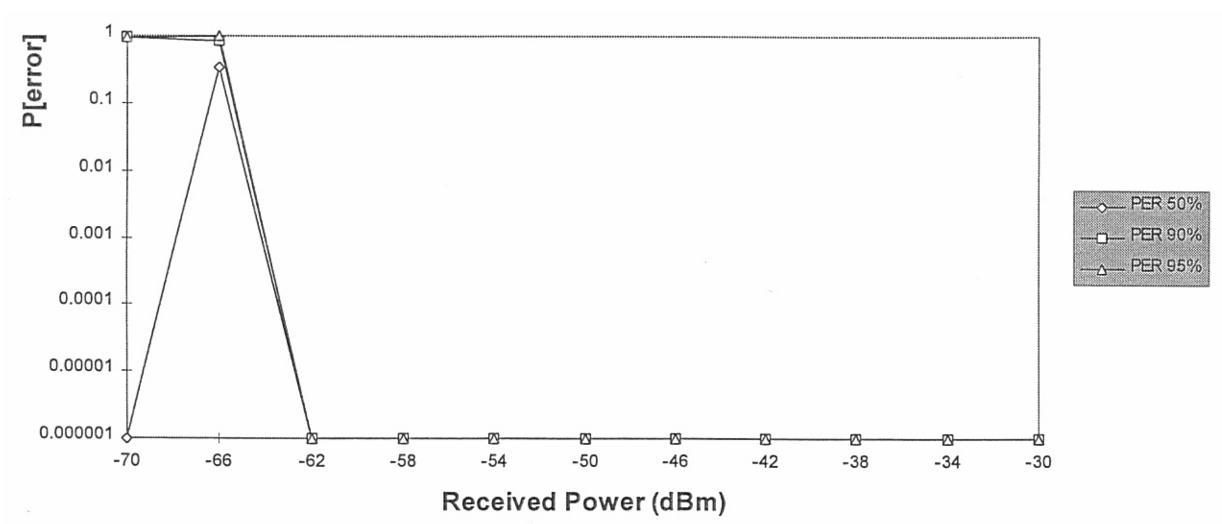

Figure 36. Percentile CER, BER, and PER vs. received signal power (SYNC data) for urban low-rise environment.

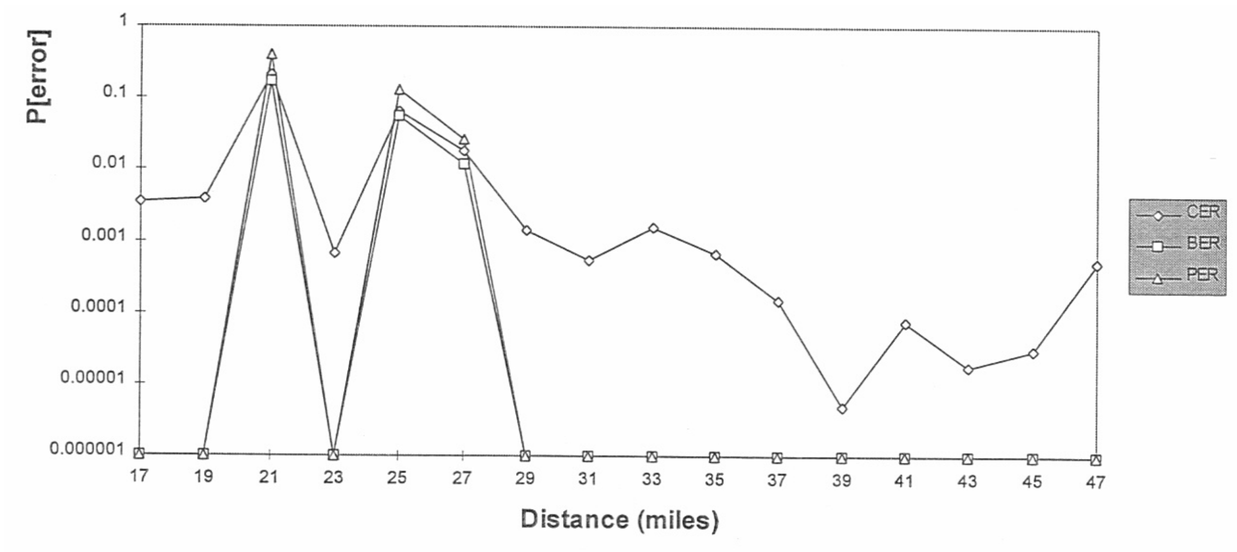

Figure 37. Mean CER, BER, and PER vs. distance from transmitter for urban low-rise environment.

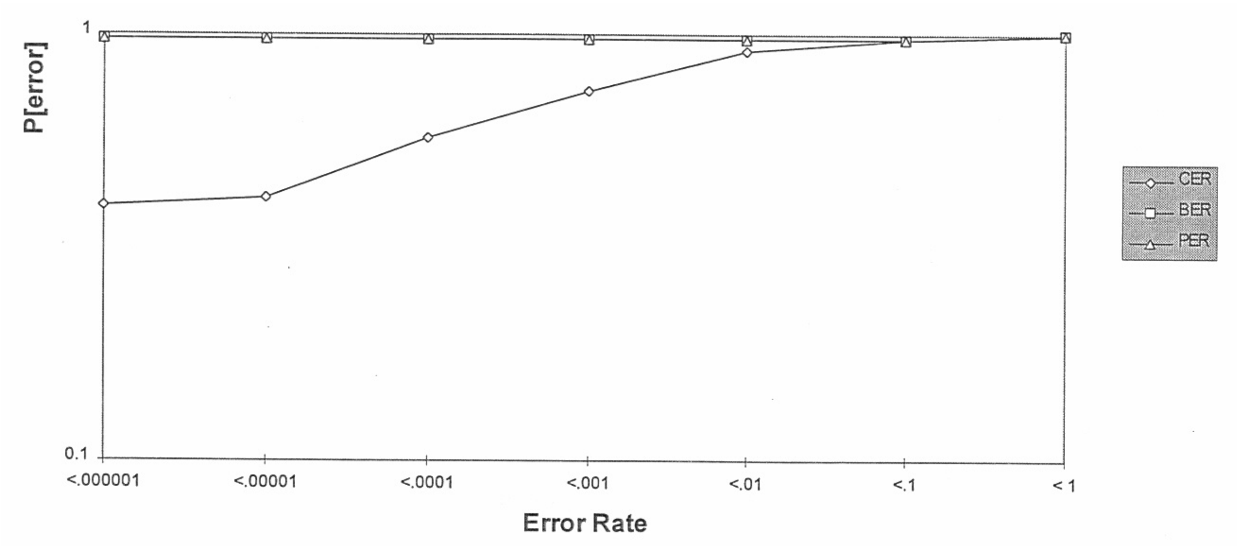

Figure 38. Cumulative CER, BER, and PER vs. error rate for urban low-rise environment.

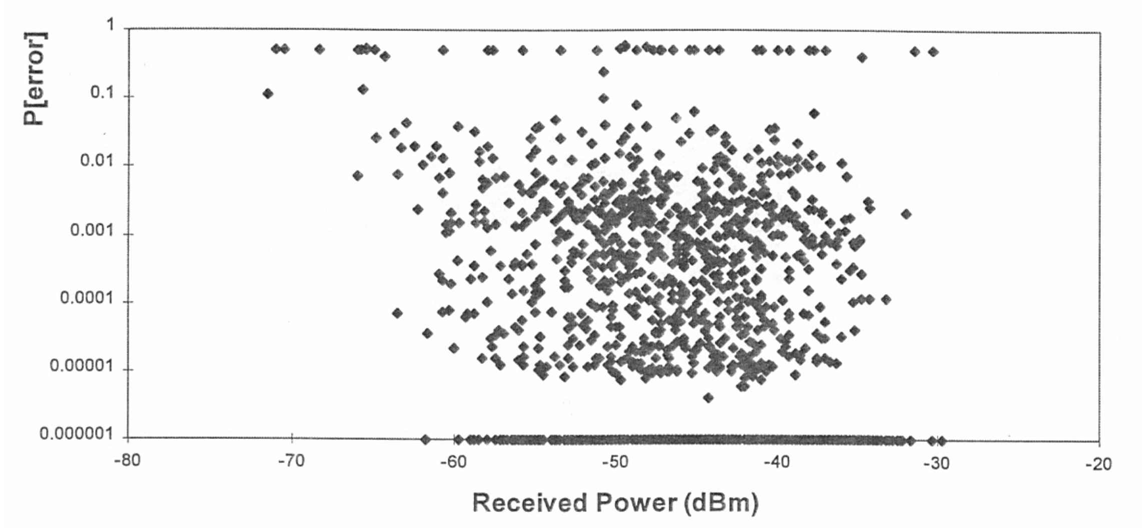

Figure 39. Channel error rates vs. received signal power for urban low-rise environment

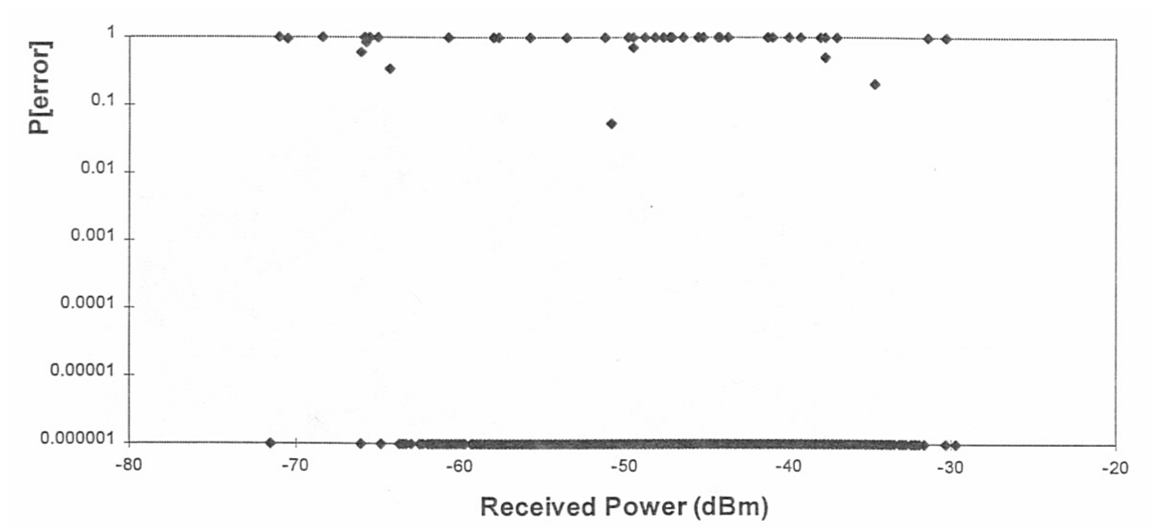

Figure 40. Packet error rates vs. received signal power for urban low-rise environment.

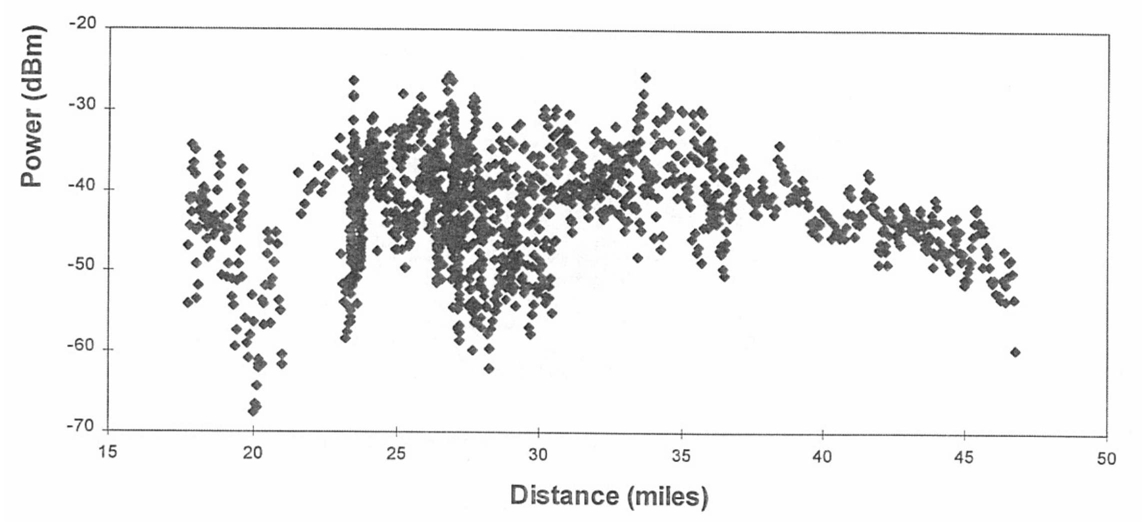

Figure 41. Received signal power vs. distance from transmitter for urban low-rise environment.

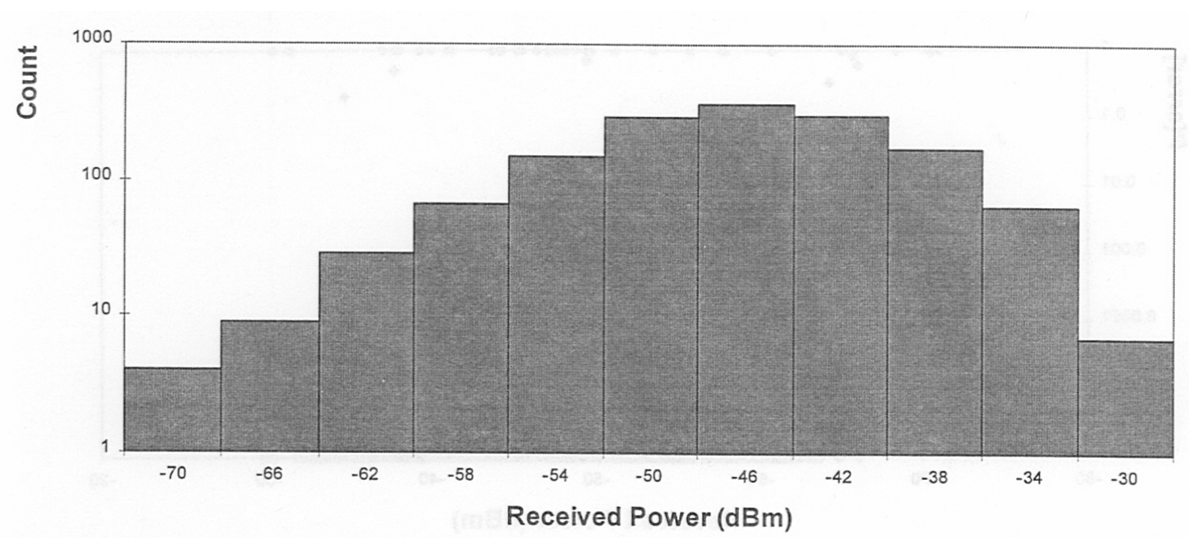

Figure 42. Measurement count vs. received signal power for urban low-rise environment.

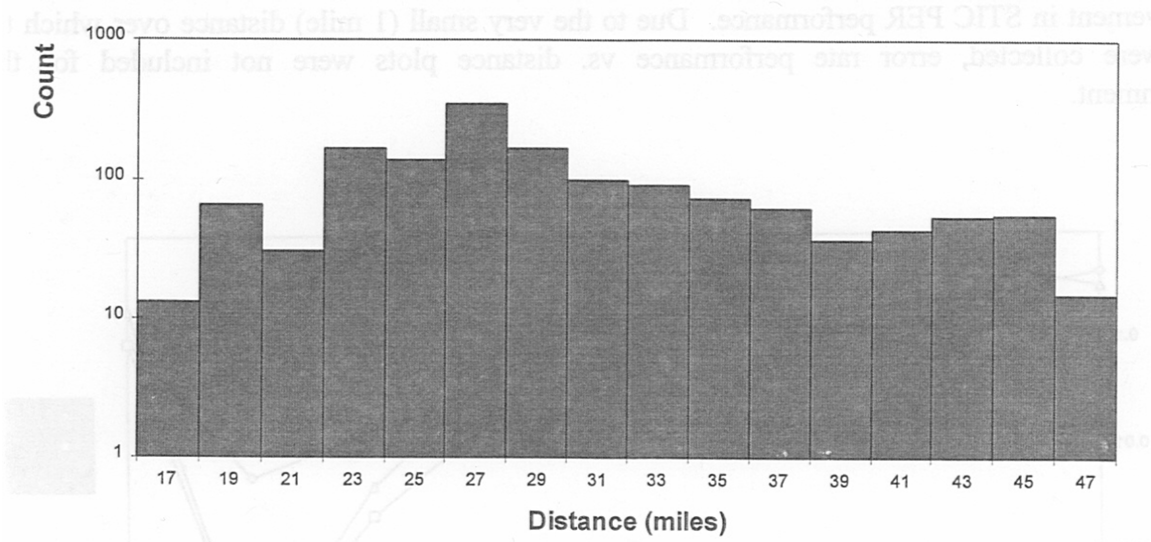

Figure 43. Measurement count vs. distance from transmitter for urban low-rise environment.

4.3.4 Urban High-rise Environment

The urban high-rise environment data set was collected over paths totaling 16.4 miles and at distances between 25.5 and 26.5 miles from the transmitter. The data set consisted of 276 signal-power and STIC error-rate measurements.

The urban high-rise environment data were collected on the streets of downtown Denver, Colorado in the deep canyons formed by the rows of tall buildings. These artificial canyon walls were typically 5 or more stories high and provided a severe multipath and fading environment for the STIC receiver. This section of downtown Denver was a reasonably square area, approximately one-half mile on each side. In order to maintain a consistent environment and not leave the boundaries of the high-rise sector, the measurement van was driven up and down adjacent streets, within the confines of the tall buildings. The path was then reversed, driving on the opposite side of the streets previously driven. When the high-rise area was traversed, the streets perpendicular to the first set were driven and the process was repeated.

The Denver high-rise environment may not be typical of the reception environment of most high-rise areas. A typical FM transmitter, located atop a tall building in a high-rise area, may present a much greater signal level than a transmitter located 26 miles away and produce significantly improved system performance.

As expected, STIC performance degraded in the urban high-rise environment (Figures 43-53). Similar to the rural plains data, removal of the out-of-sync data resulted in an 8- to 10-dB improvement in STIC PER performance. Due to the very small (1 mile) distance over which the data were collected, error rate performance vs. distance plots were not included for this environment.

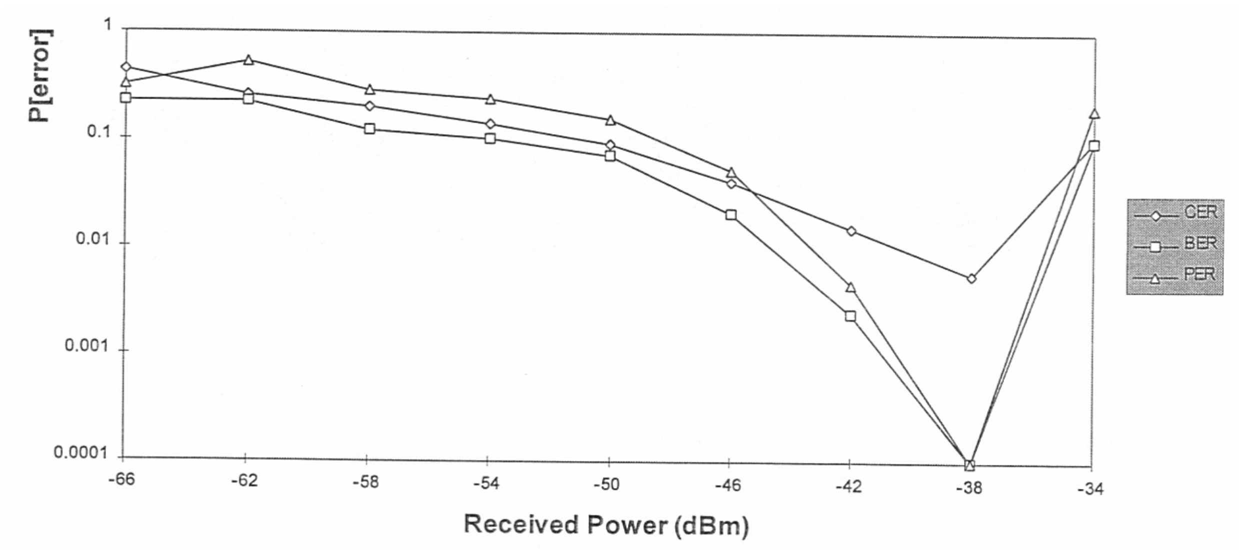

Figure 44. Mean CER, BER, and PER vs. received signal power for urban high-rise environment.

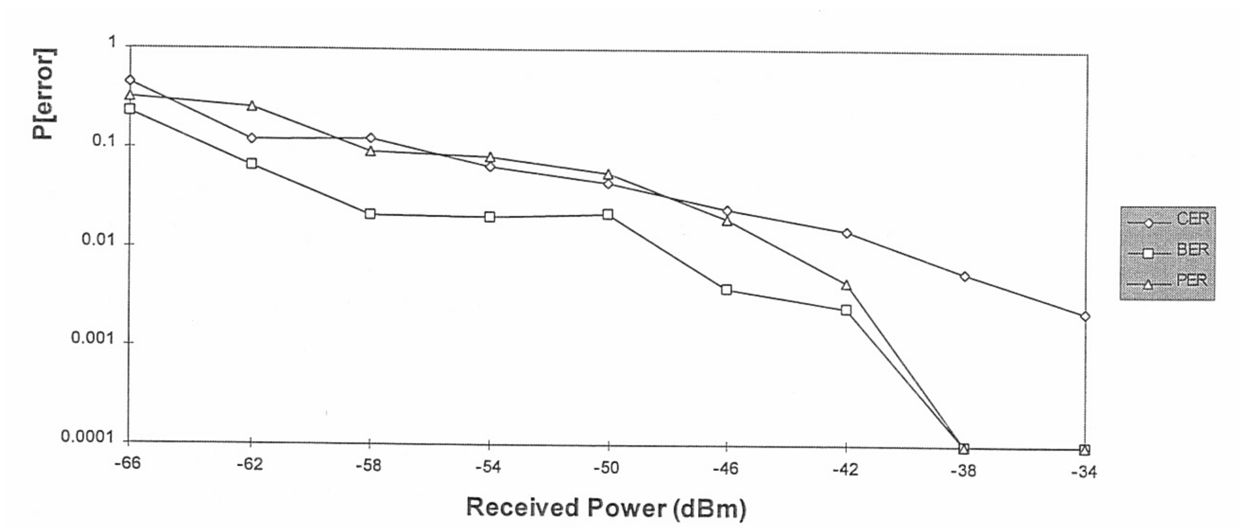

Figure 45. Mean CER, BER, and PER vs. received signal power (SYNC data) for urban high-rise environment.

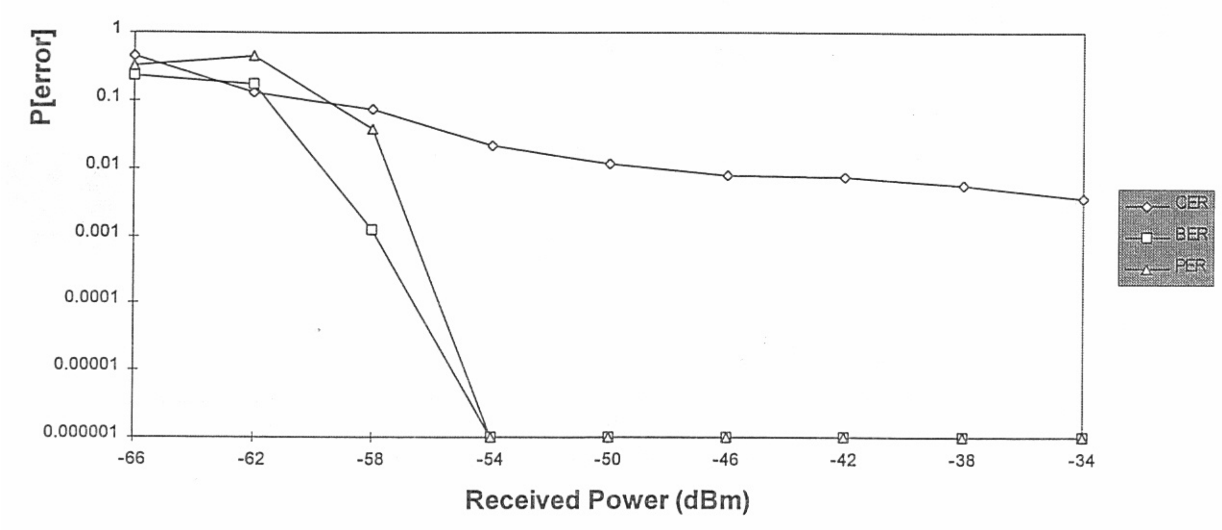

Figure 46. Median CER, BER, and PER vs. received signal power for urban high-rise environment.

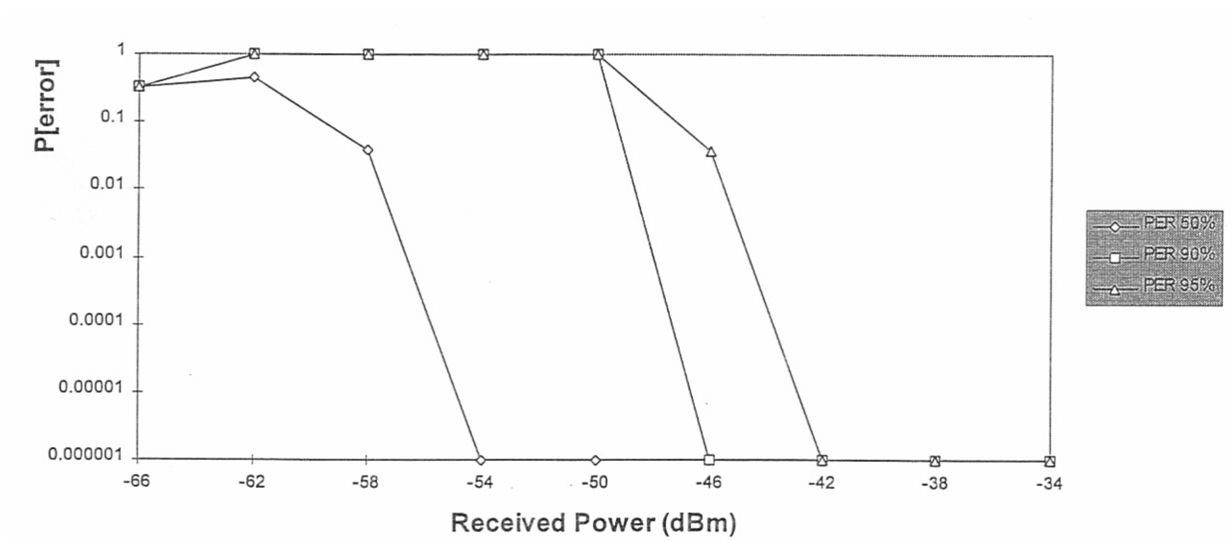

Figure 47. Percentile CER, BER, and PER vs. received signal power for urban high-rise environment.

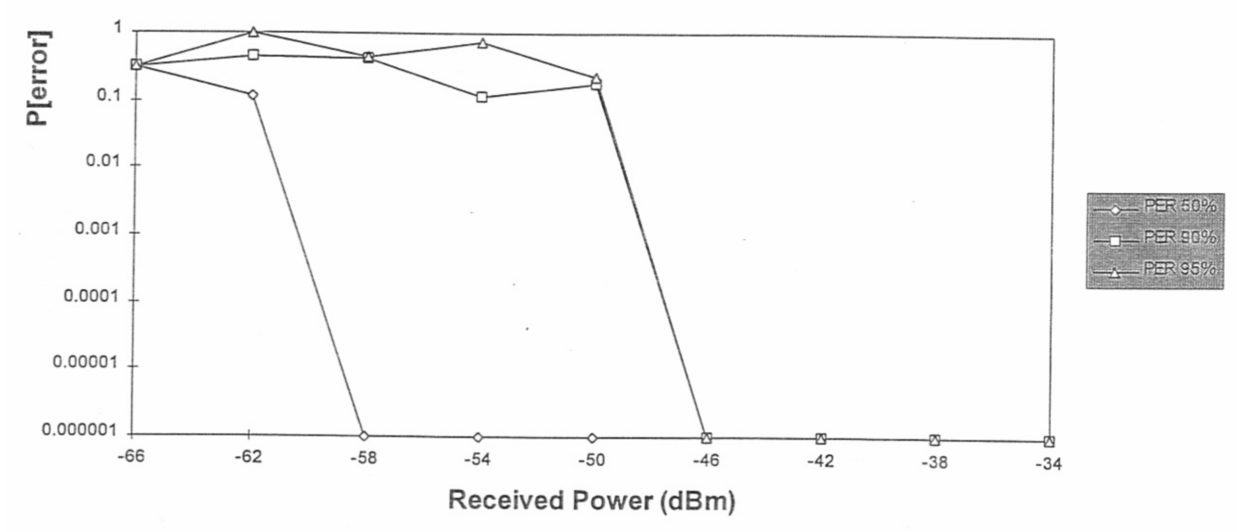

Figure 48. Percentile CER, BER, and PER vs. received signal power (SYNC data) for urban high-rise environment.

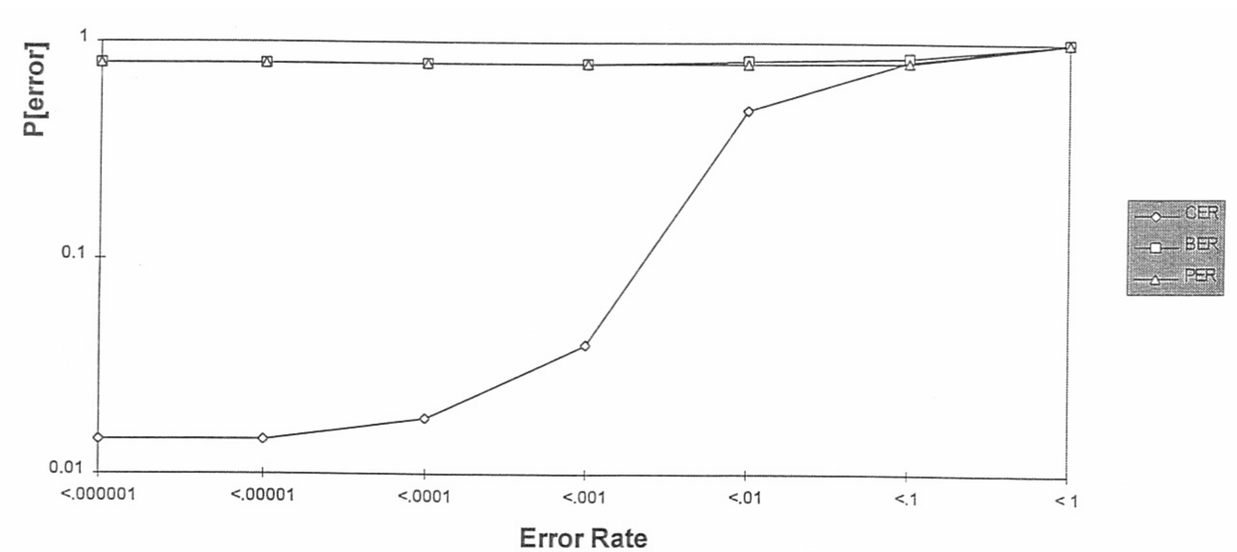

Figure 49. Cumulative CER, BER, and PER vs. received signal power for urban high-rise environment.

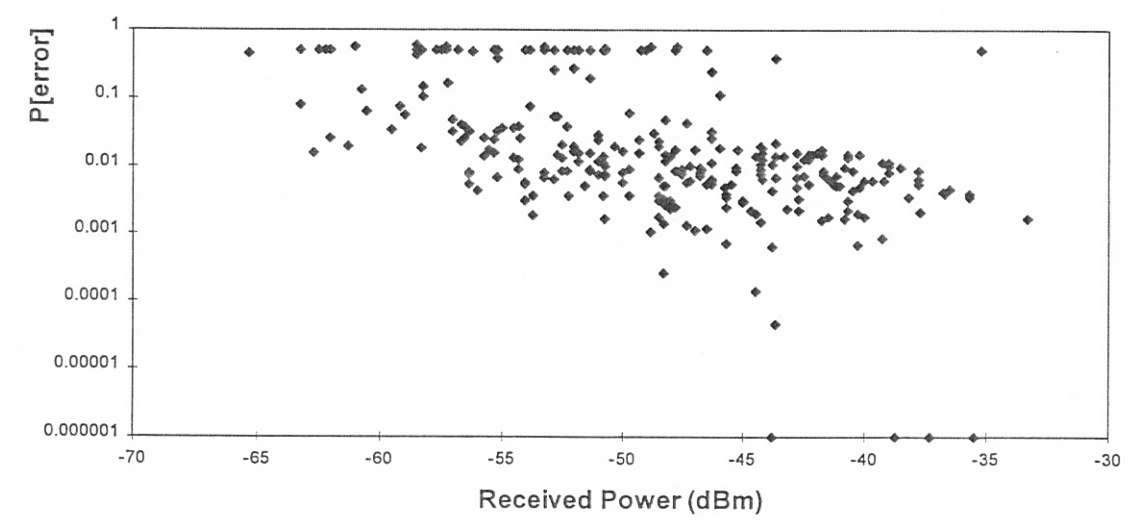

Figure 50. Channel error rates vs. received signal power for urban high-rise environment.

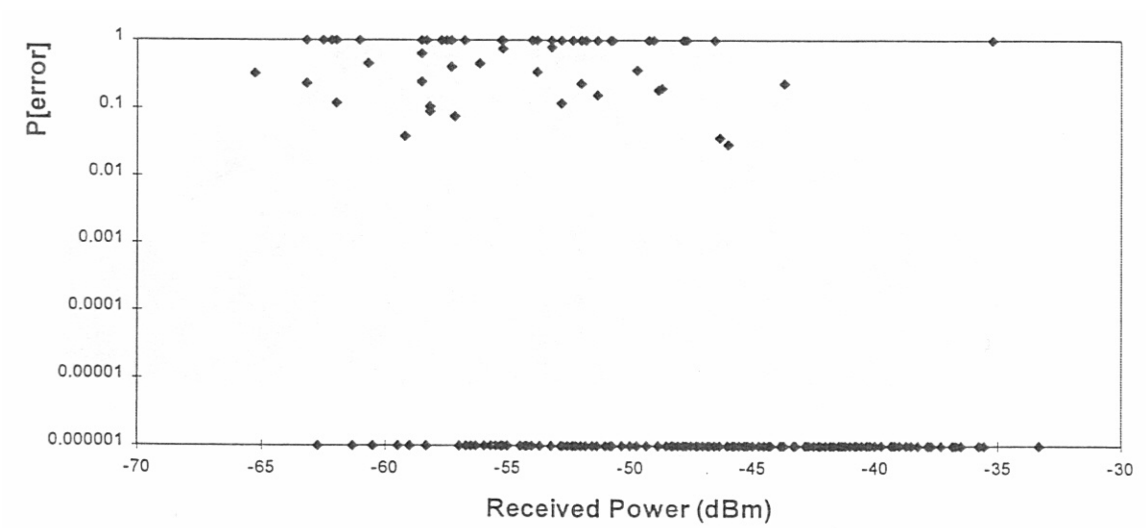

Figure 51. Packet error rates vs. received signal power for urban high-rise environment.

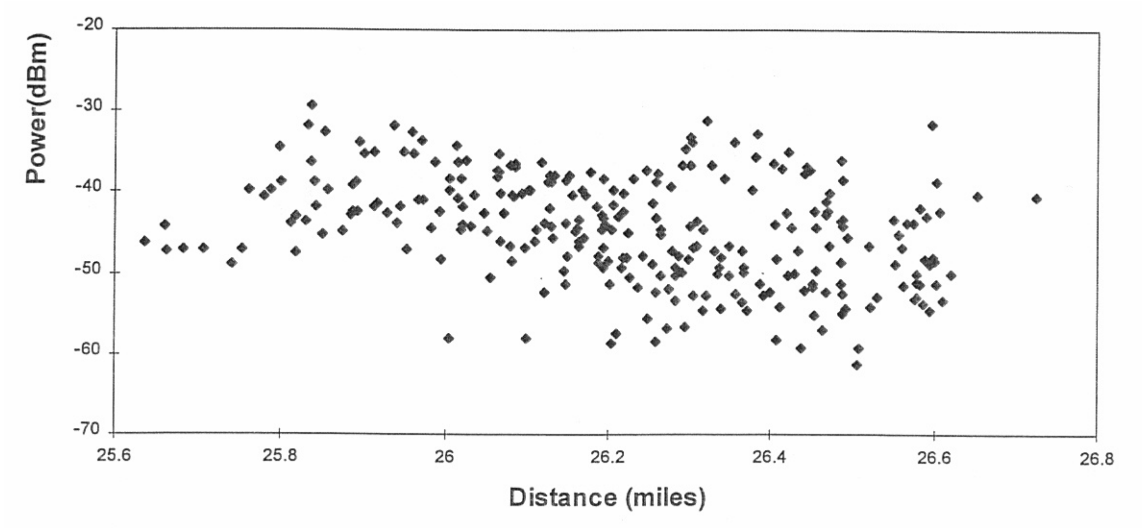

Figure 52. Received signal power vs. distance from transmitter for urban high-rise environment.

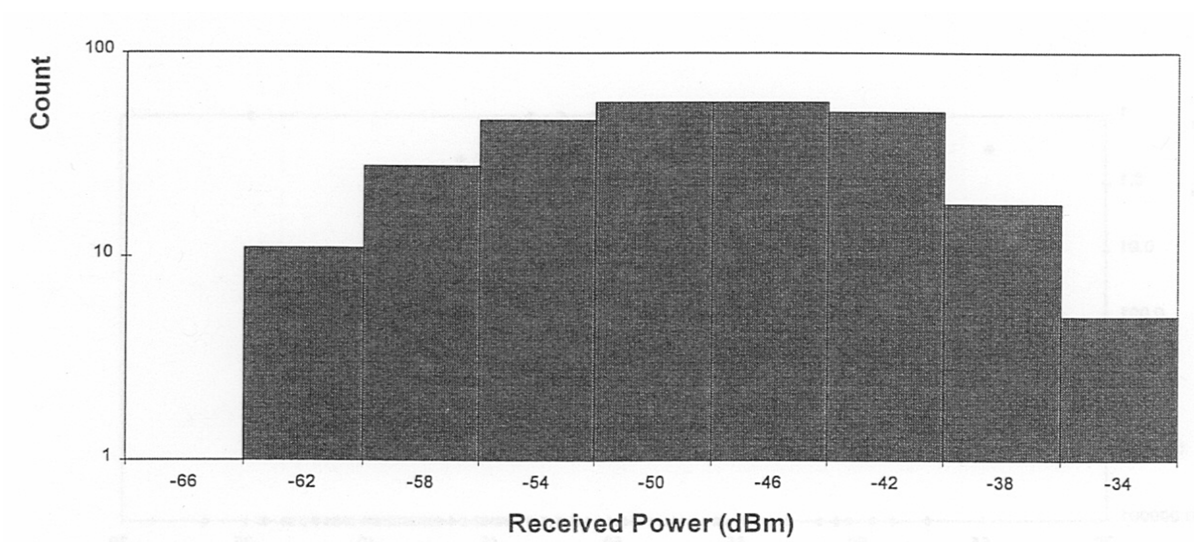

Figure 53. Measurement count vs. received signal power for urban high-rise environment.